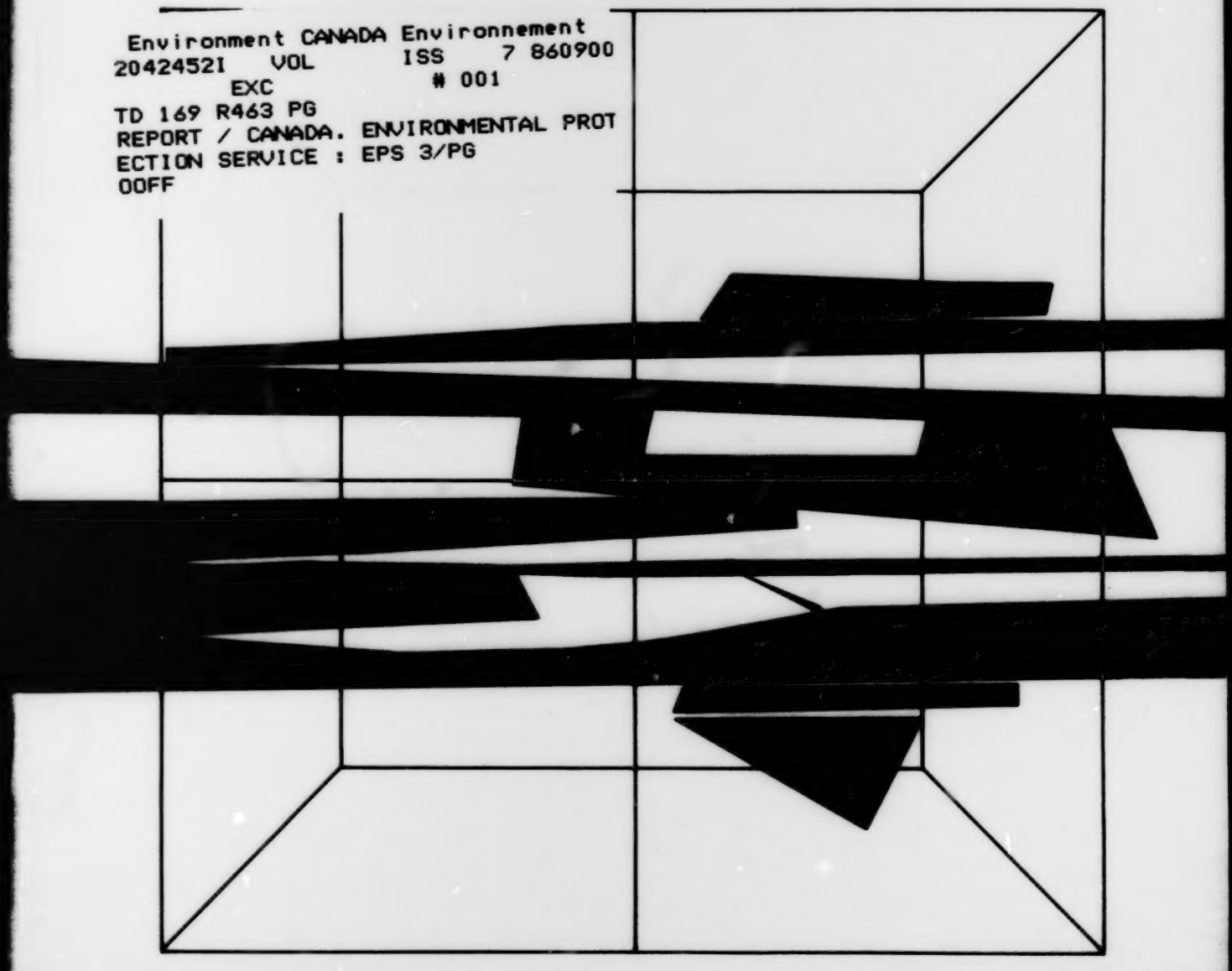
Evaluation of Solid Residues from Atmospheric Fluidized Bed Combustion, 1983/84

Report EPS 3/PG/7
September 1986

Environment CANADA Environnement
20424521 VOL ISS 7 860900
EXC # 001
TD 169 R463 PG
REPORT / CANADA. ENVIRONMENTAL PROT
ECTION SERVICE : EPS 3/PG
OOFF



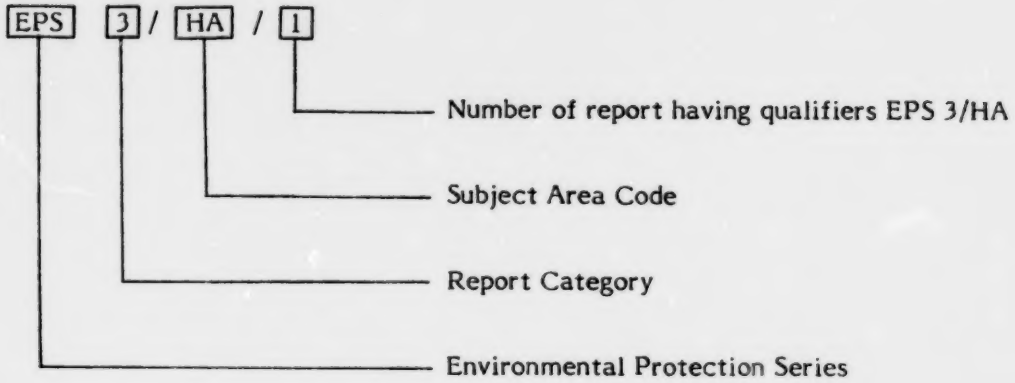
Environment Canada Environnement Canada

Canada

87-00450/

ENVIRONMENTAL PROTECTION SERIES

Sample Number:



Categories

1	Regulations/Guidelines/Codes of Practice
2	Problem Assessments and Control Options
3	Research and Technology Development
4	Literature Reviews
5	Surveys
6	Social, Economic and Environmental Impact Assessments
7	Surveillance
8	Policy Proposals & Statements
9	Manuals

Subject Areas

AG	Agriculture
AP	Airborne Pollutants
AT	Aquatic Toxicity
CC	Commercial Chemicals
CE	Consumers and the Environment
FP	Food Processing
HA	Hazardous Wastes
IC	Inorganic Chemicals
MA	Marine Pollution
MM	Mining & Mineral Processing
NR	Northern Regions
PF	Paper and Fibres
PG	Power Generation
PN	Petroleum and Natural Gas
SP	Oil & Chemical Spills
SRM	Standard Reference Methods
TS	Transportation
UP	Urban Pollution

New subject areas and codes are introduced as they become necessary. A list of EPS reports may be obtained from Environmental Protection Publications, Conservation and Protection, Environment Canada, Ottawa, Ontario, Canada, K1A 0E7.

EVALUATION OF SOLID RESIDUES FROM ATMOSPHERIC FLUIDIZED BED COMBUSTION, 1983/84

by

T.W. Constable
Wastewater Technology Centre
Environment Canada

and

R. Kissel
Dearborn Environmental Consulting Services

Report EPS 3/PG/7
September 1986

READERS COMMENTS

Readers who wish to comment on the content of this report should address their comments to -

T.W. Constable
Wastewater Technology Centre
Canada Centre for Inland Waters
P.O. Box 5050
867 Lakeshore Road
Burlington, Ontario
L7R 4A6

© Minister of Supply and Services Canada 1986
Cat. No. En 49-9/3-7E
ISBN 0-662-14969-6
BEAUREGARD PRESS LIMITED

ABSTRACT

A series of tests and analyses were conducted to examine the physical, chemical and leaching properties of solid residues produced at two Canadian atmospheric fluidized bed combustion (AFBC) installations: the Queen's University pilot-scale unit, and the first Canadian full-scale demonstration unit at Canadian Forces Base Summerside, P.E.I. Both units utilize eastern Canadian high sulphur bituminous coals for fuel and eastern Canadian limestone as a sulphur sorbent.

This study is part of an on-going program by Environment Canada to develop protocols to characterize AFBC wastes and to develop waste handling, disposal and environmental protection practices for AFBC solid residues produced at coal-fired power generating stations in Canada. To date, the study has been limited to residues generated from the combustion of high sulphur content coals in limestone beds. The reactivity and exothermic nature of these residues, and the high alkalinity and total dissolved solids levels of their leachates, are a combination of properties that are unique to these AFBC wastes in comparison to conventional combustion wastes. These residues, therefore, require special consideration in the development of safe handling, disposal and environmental protection procedures.

RÉSUMÉ

Une série d'essais et d'analyses ont été effectués pour déterminer les propriétés physiques et chimiques des résidus solides de deux installations canadiennes de combustion atmosphérique sur lit fluidisé (CALF) et dans quelle mesure ils peuvent perdre leurs constituants par lixiviation. Ces deux installations, l'unité-pilote de l'Université Queen et la première unité de démonstration en situation réelle de la base des forces armées canadiennes à Summerside, Î.-P.-É, utilisent comme combustible du charbon bitumineux à forte teneur en soufre provenant de l'est du Canada; le soufre est absorbé par de la pierre à chaux provenant de la même région.

Cette étude fait partie d'un programme entrepris par Environnement Canada pour établir des protocoles en vue de déterminer les caractéristiques des déchets de la CALF et de mettre au point des méthodes de manutention et d'élimination des déchets et de protection de l'environnement pouvant s'appliquer aux résidus solides de la CALF au Canada. Jusqu'à présent, l'étude a été limitée aux résidus de la combustion de charbon à forte teneur en soufre sur un lit de calcaire. En raison de leur réactivité et de leurs propriétés exothermiques et à cause de la forte alcalinité et de la teneur élevée en solides dissous de leurs produits de lixiviation, ces résidus possèdent des caractéristiques qui les différencient des déchets de la combustion classique et exigent donc la mise au point de méthodes spéciales de manutention, d'élimination et de protection de l'environnement.

TABLE OF CONTENTS

		Page
ABSTRACT		iii
RÉSUMÉ		iv
LIST OF FIGURES		vi
LIST OF TABLES		vii
ACKNOWLEDGEMENTS		viii
1	INTRODUCTION	1
1.1	Sample Sources	2
1.2	Preliminary Screening Tests and Analyses	5
2	EXPERIMENTAL PROGRAM	12
2.1	Determination of Physical Properties	12
2.2	Determination of Chemical Properties	12
2.3	Determination of Exothermic Properties	14
2.4	Determination of Leaching Properties	15
2.5	Quality Control	15
3	RESULTS AND DISCUSSION	17
3.1	Physical Properties	17
3.2	Chemical Properties	18
3.3	Exothermic Properties	28
3.4	Leaching Properties	40
3.5	Quality Control	48
CONCLUSIONS AND RECOMMENDATIONS		49
REFERENCES		50
APPENDIX A	LEACHING TEST RESULTS	53
APPENDIX B	QUALITY CONTROL DATA	83

LIST OF FIGURES

Figure		Page
1	RELATIVE AVERAGE COMPOSITION OF QUEEN'S AFBC SOLID RESIDUES	24
2	TEMPERATURE VARIATIONS IN THE CALORIMETER TESTS AT THREE LIQUID-TO-SOLID RATIOS	31
3	LINEAR CORRELATIONS BETWEEN HEAT OF REACTION AND CALCIUM CONTENT OF QUEEN'S FRESH SAMPLES	34
4	LINEAR CORRELATIONS BETWEEN HEAT OF REACTION AND SULPHUR CONTENT OF QUEEN'S FRESH BED MATERIAL SAMPLES	35
5	LINEAR CORRELATIONS BETWEEN HEAT OF REACTION AND CALCIUM OXIDE CONTENT OF QUEEN'S FRESH SAMPLES	36
6	LINEAR CORRELATIONS BETWEEN HEAT OF REACTION AND ACID NEUTRALIZATION CAPACITY OF QUEEN'S FRESH SAMPLES	37
7	RATIO OF HEAT OF REACTION OF RESIDUES TO HEAT OF REACTION OF PURE LIME VERSUS CALCIUM OXIDE CONTENT OF RESIDUES	38
8	NORMALIZED CUMULATIVE WEIGHT LOSS DURING LEACHING TESTS	43
9	CALCIUM CONCENTRATIONS IN QUEEN'S FRESH SAMPLE LEACHATES DURING 20 CYCLE LEACHING TESTS	46
10	SULPHATE CONCENTRATIONS IN QUEEN'S FRESH SAMPLE LEACHATES DURING 20 CYCLE LEACHING TESTS	47

LIST OF TABLES

Table		Page
1	DETAILS OF AFBC INSTALLATIONS	2
2	COMPOSITION OF COALS USED IN AFBC UNITS	4
3	COMPOSITION OF DRY HAVELOCK LIMESTONE	4
4	OPERATING CONDITIONS AT AFBC UNITS DURING SAMPLING	6
5	PRELIMINARY SCREENING TESTS AND ANALYSES ON QUEEN'S BED MATERIALS	8
6	PRELIMINARY SCREENING TESTS AND ANALYSES ON QUEEN'S AFBC CYCLONE MATERIALS	9
7	LINEAR REGRESSION ANALYSES ON ACID NEUTRALIZATION CAPACITIES OF PRELIMINARY SAMPLES	11
8	PHYSICAL PROPERTIES, pH AND ACID NEUTRALIZATION CAPACITIES OF FRESH SAMPLES	18
9	LINEAR REGRESSION ANALYSES ON ACID NEUTRALIZATION CAPACITIES OF FRESH AND ALL SAMPLES	20
10	COAL AND LIMESTONE ANALYSES	22
11	X-RAY DIFFRACTION ANALYSES OF FRESH SAMPLES	23
12	ELEMENTAL COMPOSITION OF FRESH BED MATERIAL SAMPLES	25
13	ELEMENTAL COMPOSITION OF FRESH CYCLONE MATERIAL SAMPLES	26
14	ELEMENTAL COMPOSITION OF FRESH BAGHOUSE MATERIAL SAMPLES	27
15	CALORIMETER TESTS ON FRESH SAMPLES	29
16	LINEAR REGRESSION ANALYSES ON HEATS OF REACTION OF FRESH QUEEN'S SAMPLES	33
17	SUMMARY OF RESULTS OF 20 CYCLE LEACHING TESTS WITH DEIONIZED WATER	41
18	MAXIMUM CONCENTRATIONS REACHED IN AFBC RESIDUE LEACHATES	45

ACKNOWLEDGEMENTS

Funds for this study were provided by the National Energy Program. The study was conducted at Dearborn Environmental Consulting Services in Mississauga, Ontario, and at Environment Canada's Wastewater Technology Centre (WTC) in Burlington, Ontario. The technical assistance of Mr. S.E. Sawell and Mr. W. Cunningham, and the analytical support provided by the Laboratory Services Section of the Wastewater Technology Centre, are gratefully acknowledged. The assistance of the Queen's pilot plant operating staff and CANMET personnel in obtaining the samples is also gratefully acknowledged, particularly the contributions of Dr. H.A. Becker, Mr. J.R. Stephenson, Dr. E.J. Anthony and Mr. V.V. Razbin. Special acknowledgement is given to Mr. L.A. Dwyer for his guidance and technical input during the planning and implementation of this study and the preparation of this report.

1 INTRODUCTION

The atmospheric fluidized bed combustion (AFBC) process is being developed in Canada as a viable technology for extracting energy from coal and variable quality solid fuels. In this process, coarsely crushed coal is burned in a bed of limestone that has been fluidized by jets of heated air. The direct contact between the bed material and the solid fuel permits the calcareous bed material to absorb sulphur oxides, thus reducing their emission to the atmosphere. A description of the basic features and advantages of the AFBC process is given by Becker and Code (1982).

From an environmental viewpoint, the principal advantages of AFBC include the reduction of nitrogen emissions through relatively low temperature combustion and the control of sulphur emissions from high sulphur content coals through the use of a limestone bed in the combustion zone. This eliminates the need for complex and costly flue gas desulphurization (FGD) systems for coal-fuelled boilers.

Compared to the usual residues of dry bottom ash, dry fly ash and wet FGD sludge which are normally produced from a pulverized coal-fired (PCF) facility with an FGD system, an AFBC unit burning high sulphur content coal in a limestone bed at high calcium-to-sulphur ratios generates larger volumes of dry spent bed material and, depending on the AFBC design, may produce much smaller quantities of dry fly ash. These residues differ from those generated in higher temperature PCF combustion processes in that they are not primarily silicious glassy materials. The spent bed material is a coarse, sand-sized, dry solid which contains substantial quantities of calcium sulphate, unreacted calcium oxide and trace elements (Collins, 1980). The stack or elutriated material, referred to as carryover or fly ash, consists of fine particulate that has been removed from the exhaust gases by dust collecting devices such as baghouses.

With increasing AFBC interest in Canada, a series of studies to evaluate the environmental implications of this new technology were initiated (EPS, 1982; CH2M Hill, 1982). These studies indicated that the potential problems these wastes might pose during handling and disposal were not well defined. This led to the laboratory evaluation of three AFBC wastes from a test facility using high sulphur content, Canadian Maritimes fuels and limestone (EPS, 1985). The evaluation indicated that these wastes possessed a variety of unusual properties such as very high solubility, alkalinity, and exothermic reactivity when in contact with water. The exothermic characteristic appeared to be caused by the unslaked lime (crystalline calcium oxide) content of these wastes. The reaction was, at times, unpredictably fast.

These waste properties suggested that environmentally safe waste handling and disposal practices which differ significantly from those of more conventional coal combustion residues, may need to be developed. However, due to the limited number and nature of the samples evaluated, it was not known to what degree the observed waste characteristics would be shared by other eastern Canadian coal/limestone AFBC wastes. In this study, solid residue samples from two new Canadian AFBC units burning high sulphur content coals in limestone beds were examined in order to verify the results of the previous study, and to continue the development of a data base on AFBC residue properties which will permit comparisons with conventional PCF and PCF/FGD wastes to be made. These objectives were achieved by conducting detailed chemical analyses to determine the elemental and crystalline composition of the solid wastes, performing laboratory tests to quantify the exothermic properties of the wastes, and conducting batch leaching tests to investigate the mobilization of elements from the solid wastes.

1.1 Sample Sources

The solid wastes characterized in this study were produced at the Queen's University AFBC Pilot Plant in Kingston, Ontario and the full-scale AFBC unit at Canadian Forces Base (CFB) Summerside in Summerside, P.E.I. A comparison of the major details of these installations is given in Table 1.

TABLE 1 DETAILS OF AFBC INSTALLATIONS (Becker et al., 1984)

		Summerside*	
	Queen's	Preferential Bed	Secondary Bed
Bed Size (m)	0.38 x 0.41	1.2 x 2.9	1.4 x 2.9
Bed Depth** (m)	1.0	1.4	1.4
Fluid Vel. (m/s)	1.5 to 3.0	2.4	3.0
Excess Air (%)	0 to 50	25	20
Ca/S Ratio	1:1 to 4:1	3:1	3:1
Recycle Ratio	0.0 to 1.0	0.75	0.75
Run Length (h)	20 to 48	continuous	as required
Bed Level Control	overflow	extraction	extraction

* Both boilers at Summerside contain two beds. The secondary bed can be shut down while the preferential bed continues to operate. This allows adjustment for varying steam demand.

** The bed depths may not be comparable.

The AFBC unit at CFB Summerside is the first full-scale AFBC unit to be demonstrated in Canada. It consists of two boilers, each with a generating capacity of 18 000 kg/h of steam at 965 kPa (1.5 MW). It was built to operate in conjunction with an existing coal-fired steam plant to provide heating for all major buildings on the base, and also to demonstrate AFBC as a viable, clean "off-oil" technology on a commercial scale. The design fuel is high-volatile bituminous Devco coal from Nova Scotia containing approximately 20% ash and 5% sulphur. The performances of the boilers with inferior Minto Coals from New Brunswick (with about 7% sulphur), and with wood chips as a supplemental fuel providing up to 30% of the heat input, is also to be demonstrated. Limestone from the Havelock Lime Works in Havelock, New Brunswick is used as the sulphur sorbent in the beds. Information on the design coals and limestone is given in Tables 2 and 3. The contractor selection process and plant design are described in Taylor and Friedrich (1982).

The pilot plant at Queen's University was constructed in 1979 through contract funding by CANMET (Energy, Mines and Resources Canada) to investigate atmospheric fluidized bed combustion. During the last few years, one of its uses has been to provide a data base for the Summerside demonstration plant by conducting combustion trials using Nova Scotia and New Brunswick coals and Havelock limestone. Details of the construction and operation of the pilot plant, and the results of the combustion trials, are given in Becker and Code (1982, 1983).

Two groups of samples were obtained for testing and analyses during this study. The first group consisted of sub-samples of bed and cyclone materials from 18 runs conducted at the Queen's pilot plant between January 12 and March 16, 1983. Samples of baghouse materials from these runs were not available. The samples had been stored in plastic bags for several months prior to being shipped to the Wastewater Technology Centre (WTC) for the preliminary screening tests. Samples selected for testing were chosen from those collected near the end of each run when steady-state conditions had been achieved in the AFBC unit. The solid fuels and sorbent material used during these runs were Minto and Devco coals and Havelock limestone.

The second group of samples consisted of six sets of bed, cyclone and baghouse materials from the Queen's unit, and one set of bed and baghouse materials from the Summerside unit. The samples from the Queen's unit were collected by Queen's pilot plant operating staff during steady state conditions in six test runs conducted between November 15, 1983 and January 5, 1984. These samples are referred to in this report as "fresh" samples, to differentiate them from the samples used in the preliminary screening

TABLE 2 COMPOSITION OF COALS USED IN AFBC UNITS

	Minto (1)	Devco (2)	Evans (3)
Proximate Analysis (%)			
Moisture	0.0	0 to 10	1.9 to 2.3
Ash	17.4 ± 1.4	16 to 22	11.7 to 17.0
Volatile Matter	33.7 ± 0.2	33.5	34.1 to 35.4
Fixed Carbon	49.3 ± 0.9	47.2	48.9 to 53.4
Ultimate Analysis (%)			
Carbon	66.3 to 68.3	64.2	67.6 to 71.1
Hydrogen	4.1 to 4.3	4.0	4.25 to 4.52
Sulphur	7.4 to 8.0	5.0 to 6.0	6.36 to 6.81
Nitrogen	0.8 to 0.9	1.0	1.14 to 1.24
Ash	17.4 to 18.7	16 to 22	11.7 to 12.3
Oxygen (by difference)	1.8 to 2.0	6.0	3.59 to 5.60
Ash Analysis (%)			
Silicon	13.2 to 19.4	18.6	10.9 to 14.2
Aluminum	5.5 to 5.9	13.5	6.5 to 8.8
Iron	26.2 to 30.2	18.9	12.4 to 27.6
Titanium	0.4	0.7	0.2 to 0.4
Phosphorus	0.9	0.3	0.2 to 0.6
Calcium	2.7 to 2.8	0.7	3.4 to 12.0
Magnesium	0.03 to 0.5	0.3	0.4 to 1.0
Sulphur	1.4	0.3	2.3 to 9.4
Sodium	0.1 to 2.1	2.0	0.5 to 2.7
Potassium	0.1 to 0.7	1.9	1.1 to 1.3

References:
(1) Becker and Code, 1983
(2) Taylor and Friedrich, 1982
(3) Becker et al., 1984

TABLE 3 COMPOSITION OF DRY HAVELOCK LIMESTONE (Taylor and Friedrich, 1982)

	Composition (%)
Loss-on-ignition at 980°C	42.6
Calcium	39.5
Silicon	0.63
Magnesium	0.41
Iron	0.12
Aluminum	0.08
Sulphur	<0.01

tests. Details on sampling locations in the unit and sampling procedures are given in Becker and Code (1982) and Becker et al. (1984). The solid fuel used during the six runs was high sulphur bituminous coal from Evans Coal Mines Limited, St. Rose, Inverness County, Nova Scotia (Table 2). The sorbent material was Havelock limestone. Sub-samples of this coal and limestone were also provided by Queen's University staff.

The set of bed and baghouse material samples from the Summerside unit were collected by CANMET staff during acceptance testing on November 24, 1983, when Devco Prince high sulphur bituminous coal was combusted with Havelock limestone.

All samples in the second group were placed into sealed plastic containers immediately after collection to minimize atmospheric contact, and were mixed thoroughly prior to analysis and testing.

The operating conditions at the Queen's and Summerside AFBC units when the samples were collected are summarized in Table 4. The reported conditions include bed temperature; the percent of excess air (over theoretical stoichiometric requirements) input to the bed; the fraction of recycled cyclone dust to the total flow of cyclone dust; the molar ratio of calcium equivalent (including calcium and magnesium) in the limestone to the sulphur in the coal; and the diameter of the coal and limestone particles (equal to the diameter of the sieve opening that passes 50% of the particles by mass). The operating conditions are presented since they are expected to affect the nature and properties of the residues. This type of information has usually been omitted from other AFBC residue studies, which makes it difficult to interpret and compare results.

1.2 Preliminary Screening Tests and Analyses

A variety of combustion trials were scheduled for both the Queen's and Summerside units during 1983/84 and plans were made to obtain fresh samples from each site as the wastes were produced. In the interim, until these samples became available, bed and cyclone samples from the January to March, 1983 Queen's tests were subjected to a series of screening tests and analyses, which included batch leaching, acid neutralization capacity, total calcium, and total sulphur determinations. As was the case with the samples examined in the previous study, the possibility could not be eliminated that some atmospheric exposure or inadvertent contamination had affected some of the samples before they were tested. Nevertheless, the tests and analyses were conducted because no other samples were available. The samples used were in storage for a shorter time than previous samples and they were generated under a variety of conditions in a different combustion unit.

TABLE 4 OPERATING CONDITIONS AT AFBC UNITS DURING SAMPLING

Sample Description	Run No.*	Bed Temp. (°C)	Excess Air (%)	Cyclone Recycle Fraction	Molar Ca/S Ratio	Particle Diameter (mm)	
						Coal	Limestone
Queen's Preliminary Samples	830112M	820	-0.1	0.96	1.60	10.7	0.78
	830124M	820	-2.8	0.91	2.10	10.7	0.78
	830126M	805	1.9	0.84	4.25	10.7	0.78
	830201M	825	-1.5	0.92	2.24	6.6	0.78
	830215M	860	14.7	0.60	2.24	6.6	0.78
	830216M	865	14.9	0.52	2.92	6.6	0.78
	830217M	840	20.5	0.00	2.95	6.6	0.78
	830218M	860	24.0	0.00	2.70	19.3	1.98
	830224M	855	21.8	0.57	3.56	19.3	1.72
	830225M	940	19.3	0.54	3.10	6.6	1.72
	830226M	920	17.2	0.61	4.47	6.6	1.72
	830309D	860	21.1	0.86	3.00	6.6	1.72
	830315D	865	34.4	0.70	3.52	6.6	1.72
	830316D	850	43.6	0.76	2.27	6.6	1.72
	830322M	840	1.2	0.00	2.14	19.3	0.49
	830324M	855	0.8	0.70	1.87	19.3	0.49
	830329M	855	-1.4	0.59	3.73	19.3	0.49
	830330M	850	-9.2	0.00	3.57	19.3	0.49
Queen's Fresh Samples	831115E	861	-21.1	0.00	4.10	17.0	0.49
	831122E	879	-15.3	0.00	1.70	17.0	0.49
	831124E	863	-19.9	0.55	1.80	17.0	0.49
	831213E	873	-2.3	0.00	3.30	17.0	1.72
	831214E	881	0.0	0.61	3.10	17.0	1.72
	840105E	819	4.1	0.96	3.00	3.0	1.72
Summerside Fresh Samples	831124D	882	62.2	0.75	2.42	-	-

* Run No. = Year Month Day Coal (M = Minto, D = Devco, E = Evans)

The acid neutralization capacities of the residues were determined using ASTM C400-64 (ASTM, 1982). Cyclone materials were tested as received, but the larger particulate bed materials were ground prior to testing to give an indication of their total acid neutralization capacities, rather than their capacities during the short-term test. One gram of solid residue was added to 20 mL of water, and sufficient 0.3N H_2SO_4 (sulphuric acid) was added to the mixture until a pH of 4.4 was achieved (Tables 5 and 6). The acid neutralization capacities ranged between 9.9 and 22.3 g-equiv./kg in the spent bed materials, and between 3.4 and 16.5 g-equiv./kg in the cyclone materials. In general, the acid neutralization capacity of each bed material was about 50% higher than that of the cyclone material from the same run.

The results of the calcium and sulphur analyses on the preliminary samples indicated that the calcium and sulphur concentrations in each bed material were twice those in the cyclone material from the same run (Tables 5 and 6). The calcium content of the residues ranged from 33.8% to 47.4% in the bed material and from 8.3% to 38.6% in the cyclone materials. The sulphur content of the bed materials ranged between 5.5% and 15.9%, with an average of 11.3%, whereas the sulphur content of the cyclone materials ranged between 2.7% and 7.1%, with an average of 5.2%.

The residues were also subjected to a 24-hour batch leaching test using distilled water at a 20:1 liquid-to-solid ratio (Côté and Constable, 1983), and the leachates were analyzed for pH, conductivity, TDS, calcium and sulphate (Tables 5 and 6). For the spent bed materials, leachate pH ranged between 12.3 and 12.8, conductivity between 8.5 and 10.1 mS/cm, TDS between 4350 and 4690 mg/L, calcium between 1350 and 1700 mg/L, and sulphate between 1210 and 1470 mg/L. For the cyclone materials, leachate pH ranged between 11.9 and 12.9, conductivity between 9.7 and 10.3 mS/cm, TDS between 4450 and 5060 mg/L, calcium between 1300 and 1700 mg/L, and sulphate between 1150 and 1540 mg/L.

The results of the screening tests and analyses conducted on the bed materials are similar to those measured in the previous study. For example, the acid neutralization capacity of the two bed material samples from the previous study was 9 g-equiv./kg, their calcium contents were 29.3% and 38.7%, and their sulphur contents were 7.1% and 10.1%. Leachates from these samples under the same test conditions had an initial pH of 12, conductivity of 8 to 9 mS/cm, and TDS of about 4000 mg/L.

The results of these prescreening studies were to have been used for subsequent sample selections from test runs of the Queen's AFBC unit. For this purpose, linear correlations were sought between the acid neutralization capacity of a waste and:

TABLE 5 PRELIMINARY SCREENING TESTS AND ANALYSES ON QUEEN'S AFBC BED MATERIALS

	Solid Characteristics				Leachate Characteristics				
Run Number**	Moisture Content (%)	Acid Neutralization Capacity (g-equiv./kg)	Calcium (%)	Total Sulphur (%)	pH	Conductivity (mS/cm)	TDS (mg/L)	Sulphate (mg/L)	Calcium (mg/L)
830112M	0.05	12.6	34.90	12.88	12.76	9.90	4540	1300	1450
830124M	0.00*	13.7	35.00	11.67	12.82	9.84	4680	1290	1400
830126M	0.00*	15.3	37.50	11.61	12.65	10.01	4640	1290	1350
830201M	0.00*	12.6	36.10	14.01	12.72	9.73	4410	1340	1400
830215M	0.00*	13.5	36.30	12.88	12.83	9.79	4580	1290	1550
830216M	0.00*	14.1	37.30	12.48	12.49	9.89	4690	1210	1500
830217M	0.00*	15.3	40.20	11.42	12.56	10.06	4530	1470	1600
830218M	0.00*	17.4	39.60	10.70	12.67	9.95	4460	1300	1400
830224M	0.00*	18.2	43.70	9.99	12.70	9.85	4480	1240	1400
830225M	0.00*	20.1	44.70	8.74	12.65	9.67	4350	1320	1500
830226M	0.00*	22.3	47.40	6.26	12.32	8.46	4400	1320	1700
830309D	0.00*	14.6	36.90	9.16	12.70	9.63	4350	1340	1500
830315D	0.00*	19.8	38.40	6.63	12.60	9.52	4410	1240	1500
830316D	0.00*	17.4	37.10	5.50	12.32	9.62	4570	1230	1700
830322M	0.00*	11.6	35.30	15.30	12.70	9.69	4600	1390	1500
830324M	0.00*	9.87	33.80	15.87	12.64	8.51	4550	1780	1650
830329M	0.00*	12.1	41.90	15.41	12.52	9.66	4530	1330	1700
830330M	0.00*	13.9	36.70	12.79	12.55	9.74	4640	1310	1700

* ash was hygroscopic

** Run Number = Year Month Day Coal (M = Minto, D = Devco)

TABLE 6 PRELIMINARY SCREENING TESTS AND ANALYSES ON QUEEN'S AFBC CYCLONE MATERIALS

	Solid Characteristics				Leachate Characteristics				
Run Number**	Moisture Content (%)	Acid Neutralization Capacity (g-equiv./kg)	Calcium (%)	Total Sulphur (%)	pH	Conductivity (mS/cm)	TDS (mg/L)	Sulphate (mg/L)	Calcium (mg/L)
830112M	0.51	7.67	17.2	5.27	12.78	9.99	4700	1300	1500
830124M	0.17	8.41	19.4	6.61	12.66	9.95	4960	1300	1450
830126M	0.00*	13.8	28.6	5.71	12.27	9.68	4550	1200	1500
830201M	0.24	8.96	19.4	5.65	12.71	9.91	4510	1340	1450
830215M	0.34	9.29	21.1	5.30	12.62	9.93	4720	1380	1550
830216M	0.00*	12.0	23.6	5.86	12.88	9.77	4760	1220	1700
830217M	0.00*	11.5	25.3	5.00	12.52	9.98	4870	1480	1500
830218M	0.12	7.29	17.6	3.73	12.57	10.25	5060	1300	1450
830224M	0.16	11.5	25.5	5.59	12.75	10.04	4810	1540	1500
830225M	0.00*	11.4	26.2	4.88	12.79	9.88	4530	1390	1500
830226M	0.00*	16.5	38.6	4.86	12.42	9.94	4700	1210	1700
830309D+	0.02	6.74	15.4	4.19	12.73	10.10	4580	1310	1500
830309D+	0.02	7.90	19.3	5.07	12.80	9.82	4450	1220	1450
830315D	0.00*	9.16	21.4	5.82	12.65	9.90	4540	1240	1450
830316D	0.68	3.42	8.3	2.74	12.57	9.73	4480	1150	1300
830322M	0.34	9.54	22.8	4.85	12.72	10.03	4690	1420	1550
830324M	0.27	10.8	22.5	4.61	12.12	9.91	4660	1200	1700
830329M	0.00	13.8	29.6	7.13	11.91	9.73	4720	1410	1700
830330M+	0.03	15.4	33.9	5.28	12.75	9.86	4790	1450	1500
830330M+	0.03	15.2	32.6	6.04	12.67	9.90	4820	1450	1550

* ash was hygroscopic
** Run Number = Year Month Day Coal (M = Minto, D = Devco)
+ two time intervals

(1) the operating conditions in effect at the time that the waste was produced (Ca/S ratio, bed temperature, percent excess air, cyclone recycle fraction, limestone diameter and coal diameter);

(2) the calcium content of the waste; and

(3) the sulphur content of the waste.

Only linear correlations between these variables were examined, relationships between leachate composition and these variables were not examined since leachate characteristics were similar for all tests. The coefficients in the equation:

Acid Neutralization Capacity = A + B x Variable Parameter

were determined using linear regression analyses. The resulting values of A and B for all the regressions that were significant at the 95% confidence level are shown in Table 7. Also shown are the values for the coefficients of determination (r^2) for these equations. The coefficient of determination is equal to the ratio of the variance explained by the regression equation to the total variance in the data, and can assume values between 0 and 1. A value of $r^2 = 1$ indicates perfect linear correlation between the two variables whereas a value of $r^2 = 0$ indicates no linear correlation.

Based on the 18 pairs of preliminary samples, the acid neutralization capacity of the bed materials is linearly related to the calcium/sulphur ratio, bed temperature, percent excess air, limestone diameter, and calcium and sulphur content (Table 7). The acid neutralization capacity of the cyclone material is linearly related to the calcium/sulphur ratio, and calcium and sulphur content.

The regressions with the highest r^2 values are for calcium and sulphur content in the bed materials, and for calcium content in the cyclone materials. The increase in the acid neutralization capacity of the bed and cyclone materials with increasing calcium content is expected since the ability of a waste to neutralize acid increases with the amount of calcium it contains. The decrease in the acid neutralization capacity of the bed material with increasing sulphur content is probably due to the decreasing proportion of sulphur captured in the bed material as more calcium (in the form of limestone) is added to the bed. As coal sulphur content increases, a disproportionate amount of calcium must be added which increases acid neutralization capacity.

Since only six sets of new samples became available from the Queen's unit during 1983/84, it was not necessary to use these relationships to choose among them. Nevertheless, they provide insights into possible relationships between waste characteristics and unit operating conditions, and are helpful for interpreting the results of the subsequent tests and analyses conducted during this study.

TABLE 7 LINEAR REGRESSION ANALYSES ON ACID NEUTRALIZATION CAPACITIES OF PRELIMINARY SAMPLES

Linear Equation Evaluated: Acid Neutralization Capacity (g-equiv./kg) = A + B x Variable Value

		Variables							
		Operating Conditions						Waste Characteristics	
Residues from Queen's AFBC Unit	Coefficients	Ca/S Ratio	Bed Temperature (°C)	% Excess Air	Cyclone Recycle Fraction	Limestone Diameter (mm)	Coal Diameter (mm)	Calcium Content (%)	Total Sulphur Content (%)
Bed Material	A	8.38	-40.43	13.35		9.81		-11.10	26.19
	B	2.37	0.065	0.16	N.S.	4.96	N.S.	0.68	-0.97
	r^2	0.35	0.41	0.45		0.69		0.60	0.80
Cyclone Material	A	2.33						-0.41	1.50
	B	2.79	N.S.	N.S.	N.S.	N.S.	N.S.	0.47	1.71
	r^2	0.51						0.97	0.28

Note: N.S. = not significant at 95% confidence level

r^2 = coefficient of determination = explained variance/total variance

2 EXPERIMENTAL PROGRAM

In addition to the first group of Queen's samples which were used for screening tests and analyses, a second group of samples was subsequently obtained and characterized with a more extensive series of tests and analyses. These samples consisted of six sets of fresh Queen's bed, cyclone and baghouse samples plus one set of Summerside bed and baghouse samples. The tests and analyses conducted on these samples included some of those used in the previous AFBC waste characterization study.

2.1 Determination of Physical Properties

Tests were conducted to determine the moisture content and water holding capacity of each residue. Moisture content was determined in duplicate based on the water loss at 104°C over a 24-hour period (ASTM, 1982; Method D2216-71). Water holding capacity was determined by placing a known amount of residue in a funnel lined with Whatman Number 4 ashless filter paper and covering it with water (Stone and Kahle, 1978). The water was allowed to drain through the sample under the force of gravity until no further drainage occurred for a 5 minute period. In some cases it was necessary to lightly tap the funnel several times during the drainage period in order to obtain reproducible results. The water retained was determined by subtracting the initial dry weight from the wet weight. The water holding capacity of the sample was then calculated as the ratio of the water retained in the sample to the initial dry weight of the sample, expressed as a percentage.

2.2 Determination of Chemical Properties

The chemical characteristics of the residues were evaluated through determinations of pH and acid neutralization capacity, and through application of an extensive analytical program to determine elemental and crystalline compositions.

The pH of each residue was determined using ASTM C110-76a. This method involves the mixing of 20 grams of sample in 1 litre of distilled water. The pH is determined following a one minute period of vigorous mixing and a 20-minute settling period.

The acid neutralization capacity of each residue was determined using ASTM C400-64. The bed materials were ground prior to testing, but the cyclone and baghouse materials were tested as received.

Elemental analyses were conducted on the AFBC solid residues and also on subsamples of the coal and limestone used in the Queen's and Summerside units during

the time the residue samples were collected. The residues were also analyzed after they had been subjected to 20 leaching cycles.

The principle crystalline constituents in the residues were identified using X-ray diffraction (XRD) analyses. The diffraction patterns of all samples were obtained with K_α radiation from a copper source with a nickel filter. The main peak heights were obtained from the chart recordings which gave a relative composition in arbitrary units. These values are proportional between individual compounds, but are not directly comparable between different compounds. Calibration with $CaSO_4$ (calcium sulphate) was performed in order to obtain quantitative results of the major crystalline species of interest. The "angle" and "d" spacing used were:

Compound	Angle	Interplanar Spacing "d"
$CaSO_4$ (calcium sulphate)	25.5	3.493
$CaCO_3$ (calcium carbonate)	29.5	3.035
CaO (calcium oxide)	37.6	2.614
Fe_2O_3 (iron oxide)	33.3	2.69
SiO_2 (Quartz) (silicon dioxide)	26.7	3.339

The results of the XRD analyses provided semi-quantitative information on the composition of the solid residues, and were used to determine which compounds had to be quantified using other techniques, including X-ray fluorescence (XRF), neutron activation (NA) and various wet chemistry methods. Since little information was available on the chemical composition of the residues, and because some of the existing information was contradictory, the residues were analyzed using a wide array of techniques in order to provide a confirmatory data base on chemical characteristics.

A number of wet chemistry analyses were performed in order to determine the sulphur content and its chemical form in the residues. Wet chemistry gravimetric methods are believed to be most reliable for the quantification of sulphur compounds. Total sulphur analyses by alkaline fusion and wet chemistry, and soluble sulphate analyses by wet chemistry, were performed on all samples, many in duplicate, following ASTM C2581A. Analyses were also made for elemental sulphur using a method involving extraction by carbon disulphide, oxidation and determination of sulphate by wet chemistry (Furman, 1962). Sulphide analyses were done by iodometry (Furman, 1962).

Several techniques were used to determine the total calcium content of the samples:

(1) fusion with lithium metaborate ($LiBO_2$) followed by atomic adsorption (all samples);
(2) X-ray fluorescence (most of the samples); and
(3) neutron activation (13 samples).

The latter analyses were conducted in duplicate or triplicate on each sample to allow estimation of the analytical error variance.

The carbon contents of the samples were determined by carbon dioxide analyses (Furman, 1962) and loss-on-ignition (LOI) analyses, which were performed at 950°C.

2.3 Determination of Exothermic Properties

The results of the previous AFBC waste characterization study indicated that AFBC solid residues generated from the combustion of high sulphur content coals in limestone beds are exothermic when in contact with water. A limited amount of evidence for this heat-release property was also found during the technical literature search conducted in the previous study; however, little information was given in the literature on possible relationships between heat release and the chemical characteristics of the wastes or the operating conditions under which the wastes were generated.

To verify the results of the preliminary investigation and those reported in the technical literature, calorimeter tests (ASTM C110-76a) were used to determine the heat of reaction (loss of enthalpy per unit mass) of each sample and to examine temporal changes in heat release after slaking. A known mass of sample was added in a single motion to 600 mL of distilled water contained in a 1-litre Dewar flask (calorimeter), and the temperature of the well stirred mixture monitored until less than a 0.5°C temperature rise was observed among three consecutive readings. Each residue was hydrated as received at liquid-to-solid ratios of 3:1, 5:1 and 10:1.

Exothermic testing was also conducted using a column apparatus which consisted of an 8 cm diameter stainless steel tube (40 cm in height) lined with a teflon sleeve and covered with fibreglass insulation. Five ports are located on the side of the column at 4-cm intervals to allow temperatures in the column to be measured at various depths of residue. These ports were fitted with dial thermometers in the previous study, but were modified in this study to receive thermocouples which were interfaced to an HP 1000 computer which monitored and recorded temperatures within the column. Other

modifications to the column became necessary during the study, and are described in Section 3.3. Distilled water was added to the top of the column at a rate of 1.24 mL/min, and temperatures at the five residue depths were monitored until approximately 30 to 60 minutes after detection of a peak in the bottom thermocouple. Because of problems with pressures created within the column and solidification of the residues, a successful test using this apparatus was not completed. These problems are described in Section 3.3.

2.4 Determination of Leaching Properties

Leachates from serial batch leaching tests conducted during the previous study were generally highly alkaline (pH 10 to 12) and consisted primarily of calcium sulphate. Some evidence was found that the wastes might dissolve readily in a landfill if groundwater and/or infiltration was allowed to maintain continuous contact.

In order to verify these findings, the same serial batch leaching procedure was applied to the fresh samples from the Queen's and Summerside AFBC units. Each material was leached for 20 cycles with deionized water at a 20:1 liquid-to-solid ratio. After each 24-hour cycle, the suspended solids were separated from the leachate by centrifugation and decantation, followed by filtration through 0.45 μm filter paper. The leachate was retained for analysis, and the solids contacted with fresh deionized water for the next leaching cycle. The pH, conductivity and TDS concentrations of the leachates were determined for every cycle, and leachates from Cycles 1, 2, 5, 10 and 20 were chemically characterized.

2.5 Quality Control

Analytical protocols specifically for AFBC materials have not yet been developed. A detailed quality control program was therefore conducted on both the analyses of the solid materials and the leachates in order to verify that existing analytical methods gave acceptable results.

Since a standard reference material of AFBC solid waste was not available, a standard reference PCF coal fly ash was used in the solid material quality control program. AFBC residues do not have the same glass-like properties as fly ashes from conventional pulverized coal-fired processes because of lower combustion temperatures; therefore, they should be more readily digestable during analytical determinations. The accuracy of the AFBC solid analyses would be expected to be at least as good as that of the reference fly ash analyses.

In order to evaluate the reproducibility of the analytical techniques used in the study, replicate analyses were conducted on samples of solid wastes from the Queen's and Summerside units, both before and after leaching, and on leachates from each type of solid waste.

A quality assurance program using spiked samples was also conducted to determine the accuracy of the analytical techniques used for the leachate analyses. Twelve parameters of interest were selected. Spike levels were based on the minimum and maximum concentrations observed in leachates during the prescreening leaching tests.

3 RESULTS AND DISCUSSION

3.1 Physical Properties

The results of the moisture content analyses are given in Table 8. Moisture contents were measured to determine if residues had absorbed any moisture from the atmosphere during storage and handling prior to exothermic testing. The moisture content of the bed materials was 0.0%, and ranged from 0.00% to 0.07% in the cyclone materials and from 0.07% to 0.73% in the baghouse materials. The bed materials were difficult to measure, however, because they became hygroscopic (i.e., absorbed moisture) when heated. Since the moisture content of all samples was less than 1%, it was assumed that no significant hydration of the residues had occurred prior to testing.

The results of the water holding capacity tests are also given in Table 8. Water holding capacities were measured to give some indication of the amount of water that a landfilled waste might retain against the force of gravity before it began to release leachate. Averages in the Queen's residues ranged from 50% in the bed materials to 73% in the cyclone materials to 88% in the baghouse materials. This pattern is likely due to the decreasing particle sizes of the residues progressing from bed material to cyclone material to baghouse material. The same trend was observed in the previous study in which the water holding capacities of the bed and baghouse materials were 63% and 145%, respectively. The water holding capacities of the Summerside residues, at 39% for the bed material and 75% for the baghouse material, were lower than those of the corresponding Queen's residues. This suggests that Summerside residues would be more readily drained in a landfill than would Queen's residues, which would result in an earlier release of leachate.

Some difficulty was experienced with wetting two of the Queen's baghouse materials. The materials did not become wet when water was added, but floated on the surface of the water. It was necessary to shake the suspension in a flask to thoroughly wet the material prior to pouring it into the filter-lined funnel. This suggests that the conventional methods of dust suppression used at PCF ash disposal sites may not work satisfactorily with some AFBC residues, and that it may be difficult to hydrate some of these residues. Difficulties were also encountered during testing with swelling. Some materials when wetted increased at least 100% in volume. Because of these problems, the results of the water holding capacity tests may not be directly comparable, and may not give an accurate indication of what might occur in a field disposal situation.

TABLE 8 PHYSICAL PROPERTIES, pH AND ACID NEUTRALIZATION CAPACITIES OF FRESH SAMPLES

Material	Run No.+	Moisture Content (%)	Water Holding Capacity (%)	pH of Solid	Acid Neutralization Capacity (g-equiv./kg)
Queen's Bed Material	831115E	0.00*	38.7	12.25	15.7
	831122E	0.00*	30.8	12.13	11.5
	831124E	0.00*	33.5	12.26	11.7
	831213E	0.00*	65.1	12.49	18.4
	831214E	0.00*	63.6	12.46	19.1
	840105E	0.00*	66.3	12.50	17.5
	Mean		49.7	12.35	15.7
Queen's Cyclone Material	831115E	0.05	83.9	12.58	20.9
	831122E	0.00	69.5	12.64	14.2
	831124E	0.02	62.3	12.62	14.8
	831213E	0.07	84.5	12.56	14.6
	831214E	0.02	83.3	12.56	15.4
	840105E	0.03	56.3	12.47	9.9
	Mean	0.03	73.3	12.57	15.0
Queen's Baghouse Material	831115E	0.43	88.5	12.46	7.51
	831122E	0.73	88.8	12.07	3.26
	831124E	0.24	84.8	12.40	3.81
	831213E	0.39	85.9	12.58	3.81
	831214E	0.32	80.3	12.74	5.29
	840105E	0.59	99.2	12.68	3.32
	Mean	0.45	87.9	12.49	4.5
Summerside Bed Material	831124D	0.00*	38.6	11.97	14.5
Summerside Baghouse Material	831124D	0.07	75.2	12.69	12.1

Note: + Run No. = Year Month Day Coal (E = Evans, D = Devco)
* = ash became hygroscopic when heated
Water holding capacity measured as the weight of water retained by 50.0 grams of sample against the force of gravity, expressed as a percentage.

3.2 Chemical Properties

The results of the pH and acid neutralization capacity determinations on the solid residues are shown in Table 8. The pH of all residues was between 12.0 and 12.7, indicating the residues are very alkaline. As expected, leachates produced by water

contact with these wastes were also very alkaline. Compared to the pH values obtained in the previous study, these values are similar to those of 12.1 and 12.2 measured in the two bed material samples and are higher than the value of 10.8 measured in the baghouse material sample.

The acid neutralization capacities of the Queen's residues ranged between 11.5 and 19.1 g-equiv./kg for the bed materials, 9.9 and 20.9 g-equiv./kg for the cyclone materials, and 3.3 and 7.5 g-equiv./kg for the baghouse materials. These values are comparable to those measured in the screening tests and also to those obtained in the previous study of 9 g-equiv./kg for the bed materials and 2.7 g-equiv./kg for the baghouse material. The acid neutralization capacity of the Summerside bed material of 14.5 g-equiv./kg agrees favorably with the average of the Queen's bed materials, but the acid neutralization capacity of the Summerside baghouse material, at 12.1 g-equiv./kg, is almost three times higher than the average of the Queen's baghouse material.

The acid neutralization capacity of a residue is important from an environmental viewpoint because it defines the ability of a waste to resist changes in pH. The high acid neutralization capacities of all residues, with the exception of the Queen's baghouse materials, suggest that leachates from these wastes will remain highly alkaline until a considerable amount of water has contacted the wastes. This was verified by the results of the leaching tests (Section 3.4).

As done with the screening test results, linear regression analyses were conducted on both the six sets of fresh Queen's samples and on all 24 sets of samples (screening plus fresh) to determine whether the acid neutralization capacity of the residues could be related to unit operating conditions and waste characteristics. The regressions that are significant at the 95% confidence level and their coefficients of determination are given in Table 9. The strongest linear correlations were found between the acid neutralization capacity of all three materials and their calcium and calcium oxide content, and between the acid neutralization capacity of the bed material and sulphur content.

As noted with the screening test results, acid neutralization capacity increased with increasing calcium (and calcium oxide) content and decreasing sulphur content (Section 1.2). Linear regressions for the sulphur content of the cyclone material were significant for the 18 screening samples (Table 7) and the 6 fresh samples (Table 9) when these two sets of samples were regressed independently, but the regression was not significant when all 24 samples were considered.

TABLE 9 LINEAR REGRESSION ANALYSES ON ACID NEUTRALIZATION CAPACITIES OF FRESH AND ALL SAMPLES

Linear Equation Evaluated: Acid Neutralization Capacity (g-equiv.kg) = A + B x Variable Value

Residues from Queen's AFBC Unit	Coefficients	Variables: Operating Conditions: Ca/S Ratio	Bed Temperature (°C)	% Excess Air	Cyclone Recycle Fraction	Waste Characteristics: Calcium Content (%)	Total Sulphur (%)	CaO Content (%)
Bed Ash:	A					-16.27	31.59	1.04
-6 Fresh Samples	B	N.S.	N.S.	N.S.	N.S.	0.73	-1.47	0.36
	r^2					0.94	0.90	0.98
-All 24 Samples	A	8.32	-32.92			-5.59	26.66	
	B	2.43	0.056	N.S.	N.S.	0.53	-1.01	
	r^2	0.39	0.26			0.53	0.79	
Cyclone Material:	A					-4.94	28.21	0.11
-6 Fresh Samples	B	N.S.	N.S.	N.S.	N.S.	0.56	-2.23	0.45
	r^2					0.90	0.65	0.89
-All 24 Samples	A	4.55				0.011		
	B	2.43	N.S.	N.S.	N.S.	0.44	N.S.	
	r^2	0.28				0.95		
Baghouse Material:	A	0.77				-0.66		0.73
-6 Fresh Samples	B	1.32	N.S.	N.S.	N.S.	0.37	N.S.	0.39
	r^2	0.55				0.75		0.85

Note: N.S. = not significant at 95% confidence level
r^2 = coefficient of determination = explained variance/total variance

The results of the trace elements analyses conducted on the coals and limestone used in the AFBC units when the wastes were generated are given in Table 10. The major elements in the coals (other than sulphur; Table 2) were iron (3.3% to 3.5% for Evans coal and 3.1% for Devco coal), silica (1.0% to 1.3% and 1.9%), aluminum (0.4% to 0.5% and 1.0%) and calcium (0.3% to 0.5% and 0.1%). The limestone was composed primarily of calcium (38.3% to 40.7%), magnesium (0.2% to 1.1%), silica (0.8%), aluminum (0.2% to 0.3%) and iron (0.1%). These limestone results agree favorably with those given in Table 3 (Taylor and Friedrich, 1982).

The results of the X-ray diffraction analyses of the residue are given in Table 11. Based on these results and the other elemental and confirmatory analyses, the relative average compositions of the Queen's residues were estimated, and are shown graphically in Figure 1. Calcium oxide (CaO) and calcium sulphate ($CaSO_4$) are the major constituents of the bed and cyclone materials, but are present in much smaller fractions in the baghouse material. The high and equal CaO contents of the bed and cyclone materials suggest that the average heat release upon hydration of these materials should be equal to or greater than that of the baghouse material. This was verified in the calorimeter tests (Section 3.3). The high concentrations of CaO and silica in the residues suggest that pozzolanic reactions were responsible for the solidification of the residues in the column exothermic tests (Section 3.3).

The principal assumptions used to make the estimates shown in Figure 1 were that elemental sulphur and sulphide concentrations were negligible, the proportions of $CaSO_4$ and $CaCO_3$ in the samples could be derived from the sulphur and CO_2 analyses, and that the balance of the calcium in the residues was in the form of CaO. Calcium could have also been present in the form of calcium silicate, aluminate or ferrite. These are not common impurities in limestone, however, and no formation is expected in a fluidized bed at 850°C, since they require much higher temperatures (1500°C to 1600°C). Consequently it was assumed that these compounds were absent.

The elemental compositions of the bed, cyclone and baghouse materials are given in Tables 12, 13 and 14. The residues were composed primarily of calcium, sulphur, silicon, iron, aluminum and carbon. The calcium contents of the residues ranged from 38% to 49% in the bed materials, 27% to 44% in the cyclone materials, and 10% to 29% in the baghouse materials. Total sulphur contents ranged from 8% to 14% in the bed materials, 4% to 7% in the cyclone materials, and 4% to 6% in the baghouse materials. The total and soluble sulphur concentrations were almost identical, indicating that little or no sulphur existed in elemental form. Since this finding was at odds with the results of

TABLE 10 COAL AND LIMESTONE ANALYSES

Element	Queen's				Summerside	
	Evans Coal (83 11 15)*	Evans Coal (83 12 20)	Havelock Limestone (-6 + 20)** (84 02 01)	Havelock Limestone (-15 + 100) (84 02 01)	Devco Coal (83 11 24)	Havelock Limestone (83 11 24)
Aluminum	5210	4070	2700	2740	9530	1940
Arsenic	26.7	26.7	0.96	0.85	162	2.7
Barium	68	54	< 25	< 25	32	54
Beryllium	0.44	0.44	< 0.05	0.05	1.28	< 0.05
Boron	31.0	22.0	14.0	20.0	15.4	17.0
Cadmium	< 1	1	< 1	< 1	< 1	< 1
Calcium	4810	2900	407 000	399 000	1030	383 000
Chromium	10	8	< 1	< 1	10	< 1
Cobalt	< 5	< 5	< 5	< 5	< 5	< 5
Copper	26.6	21.9	2.6	2.5	14.2	6.5
Iron	35 200	32 700	1350	1230	31 300	1200
Lead	30	35	< 5	< 5	45	< 5
Lithium	10	8	< 2	< 2	11	< 1
Magnesium	369	300	2560	2450	486	10 900
Manganese	36	38	460	440	64	664
Molybdenum	< 20	< 20	20	< 20	< 20	< 20
Nickel	11	11	9	8	11	13
Phosphate	240	240	< 100	< 100	180	120
Potassium	500	500	100	100	1500	< 100
Silica	13 400	10 000	8320	8240	18 500	7910
Silver	< 0.5	< 0.5	< 0.5	< 0.5	< 0.5	< 0.5
Sodium	1100	1100	< 100	< 100	300	< 100
Strontium	28.5	24.0	16.0	14.0	26.7	200
Titanium	349	297	159	154	426	141
Vanadium	33.7	36.9	< 0.5	< 0.5	14.7	4.5
Zinc	290	388	10	10	61	18
Zirconium	14	12	7	7	12	7

Note: all analyses expressed in mg/kg
* date of sampling
** particle size range (mesh size)

TABLE 11 X-RAY DIFFRACTION ANALYSES OF FRESH SAMPLES

Material	Run No.	Composition (%) $CaSO_4$	CaO	$CaCO_3$	$Ca_3(PO_4)_2$	Fe_2O_3	Other (mainly SiO_2 and silicates)	Loss-on-Ignition (CO_2)
Queen's Bed	831115E	47.6	39.5	2.5	0.2	2.1	5.1	1.6
	831122E	56.0	29.9	1.1	0.2	3.0	5.5	0.7
	831124E	57.6	30.0	1.6	0.2	2.6	5.0	0.2
	831213E	41.2	50.0	2.0	0.1	1.6	5.1	1.3
	831214E	42.2	50.3	2.5	0.1	1.5	4.8	0.0
	840105E	37.5	44.1	3.6	0.1	2.1	10.7	0.0
	Mean	47.0	40.6	2.2	0.2	2.2	6.0	0.6
Queen's Cyclone	831115E	13.9	43.8	16.4	0.1	4.2	7.2	9.8
	831122E	22.2	28.9	6.8	0.3	8.9	11.0	15.7
	831124E	28.2	37.3	5.6	0.2	6.0	9.0	10.2
	831213E	23.5	32.7	6.4	0.3	9.3	10.5	10.4
	831214E	29.7	35.5	3.8	0.2	8.6	9.8	6.4
	840105E	29.4	22.1	1.6	0.2	11.5	22.9	5.8
	Mean	24.5	33.4	6.8	0.2	8.1	11.7	9.7
Queen's Baghouse	831115E	13.1	15.1	8.4	1.1	23.9	23.5	10.5
	831122E	13.8	6.3	3.0	1.4	29.8	30.6	10.4
	831124E	18.6	8.3	3.0	1.2	31.5	26.7	10.4
	831213E	17.7	7.9	3.2	1.6	28.9	28.7	8.8
	831214E	23.8	14.5	1.6	1.3	25.2	24.5	5.5
	840105E	16.7	6.7	3.2	0.8	23.7	25.6	20.3
	Mean	17.3	9.8	3.7	1.2	27.2	26.6	11.0
Summerside Bed	831124D	47.6	35.9	0.8	0.1	1.8	10.9	0.0
Summerside Baghouse	831124D	24.4	26.4	4.8	0.3	10.2	19.9	8.7

Run No. = Year Month Day Coal (E = Evans, D = Devco)

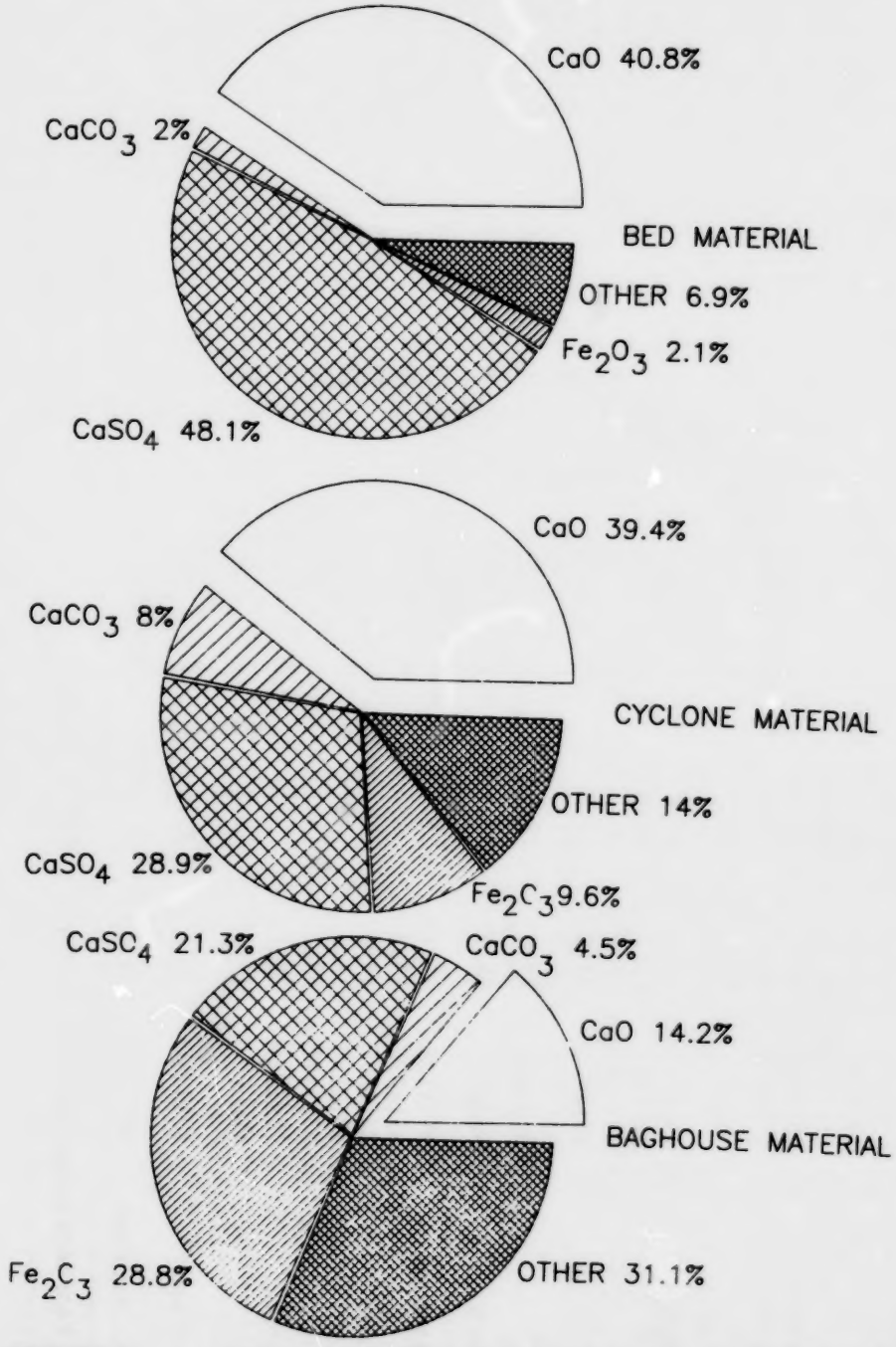


FIGURE 1 **RELATIVE AVERAGE COMPOSITION OF QUEEN'S AFBC SOLID RESIDUES**

TABLE 12 ELEMENTAL COMPOSITION OF FRESH BED MATERIAL SAMPLES

	Queen's						Summerside
Element	831115E	831122E	831124E	831213E	831214E	840105E	831124D
Major Components (%)							
Aluminum	0.50	0.58	0.57	0.44	0.49	1.50	1.42
Calcium	44.1	37.9	39.5	48.9	48.1	44.5	41.0
Iron	1.76	2.69	2.55	1.35	1.65	1.78	1.65
Silicon	1.28	1.36	1.48	1.30	1.58	3.11	3.09
Sulphur	10.88	13.20	13.60	9.24	9.48	8.48	10.08
Loss-on-Ignition	2.7	1.2	0.9	2.2	1.0	0.9	0.0
Minor Components (µg/g)							
Arsenic	29.0	54.9	50.7	325	23.9	25.2	310
Barium	81.0	127	112	80.0	91.1	139	154
Beryllium	< 0.05	< 0.05	< 0.05	< 0.05	< 0.05	< 0.05	0.11
Boron	22.4	34.6	49.7	21.9	22.2	41.6	24.6
Cadmium	< 1	< 1	< 1	< 1	< 1	< 1	< 1
Chromium	2	4	5	3	3	29	10
Cobalt	< 5	< 5	< 5	< 5	< 5	< 5	< 5
Copper	8.7	22.5	22.7	12.6	12.3	14.9	7.7
Lead	< 5	< 5	< 5	< 5	< 5	160	45
Lithium	5	8	9	6	4	10	8
Magnesium	3270	2980	3040	3740	3770	4700	5350
Manganese	500	453	464	597	583	585	849
Molybdenum	< 20	< 20	< 20	< 20	< 20	< 20	< 20
Nickel	27	29	31	27	28	30	27
Phosphorus	350	480	410	300	280	250	290
Potassium	900	900	900	900	1000	3700	2800
Rubidium	< 10	10	10	10	10	20	10
Silver	< 5	< 5	< 5	< 5	< 5	< 5	< 5
Sodium	1100	1400	900	800	1100	1700	1300
Strontium	36.7	44.7	29.1	7.7	16.7	23.4	123
Thorium	1.0	1.0	0.9	0.5	0.7	1.2	< 0.01
Titanium	365	466	401	320	319	507	574
Uranium	2.8	3.4	3.3	2.6	2.4	2.4	< 0.05
Vanadium	19.4	41.3	35.5	14.9	12.1	15.6	8.8
Zinc	189	287	347	215	260	588	209
Zirconium	15	17	15	16	15	21	20

Run Number = Year Month Day Coal (E = Evans, D = Devco)

TABLE 13 ELEMENTAL COMPOSITION OF FRESH CYCLONE MATERIAL SAMPLES

	Queen's					
Element	831115E	831122E	831124E	831213E	831214E	840105E
Major Components (%)						
Aluminum	0.67	1.12	0.92	1.31	1.22	3.10
Calcium	43.8	30.8	36.0	35.3	38.4	26.9
Iron	3.18	6.64	4.73	7.88	6.94	9.57
Silicon	2.01	3.62	3.00	3.53	3.15	5.97
Sulphur	3.60	5.60	7.00	5.88	6.68	6.88
Loss-on-Ignition	17.0	18.7	12.6	13.2	8.1	6.5
Minor Components (µg/g)						
Arsenic	6.1	18.3	17.9	25.1	26.1	55.1
Barium	128	171	149	220	160	245
Beryllium	< 0.05	0.25	0.09	0.25	0.16	0.55
Boron	40.7	58.0	53.7	71.1	65.1	82.1
Cadmium	3	12	8	14	13	26
Chromium	< 1	5	12	< 1	7	51
Cobalt	< 5	< 5	< 5	< 5	< 5	< 5
Copper	25.7	35.2	32.7	39.7	32.8	43.1
Lead	35	95	75	90	60	250
Lithium	8	14	12	15	11	29
Magnesium	2930	2480	2910	2470	2730	8350
Manganese	544	394	495	459	501	761
Molybdenum	< 20	< 20	< 20	< 20	< 20	< 20
Nickel	28	37	36	37	38	48
Phosphorus	340	510	420	590	530	520
Potassium	1400	2200	1900	2100	2400	8200
Rubidium	10	< 10	20	< 10	10	50
Silver	< 5	< 5	< 5	< 5	< 5	< 5
Sodium	1600	2400	1800	2600	2700	4200
Strontium	13.8	31.9	5.9	8.7	7.1	3.1
Thorium	0.7	1.4	0.9	1.3	0.9	2.5
Titanium	357	512	430	517	467	1050
Uranium	2.6	3.2	1.6	3.0	2.6	1.8
Vanadium	17.4	51.2	37.6	55.5	44.2	75.5
Zinc	483	999	872	858	898	2410
Zirconium	12	16	14	16	20	33

Run Number = Year Month Day Coal (E = Evans)

TABLE 14 ELEMENTAL COMPOSITION OF FRESH BAGHOUSE MATERIAL SAMPLES

	Queen's						Summerside
Element	831115E	831122E	831124E	831213E	831214E	840105E	831124D
Major Components (%)							
Aluminum	4.32	4.91	4.09	5.48	4.61	4.13	3.09
Calcium	18.3	10.0	12.3	12.8	19.1	10.9	29.0
Iron	17.3	22.9	20.3	20.3	18.5	17.3	7.59
Silicon	6.61	8.43	7.23	7.85	6.28	7.37	5.48
Sodium	1.03	1.21	0.80	1.34	1.05	0.87	0.21
Sulphur	3.68	4.28	4.48	4.60	5.88	4.20	5.88
Loss-on-Ignition	14.2	11.7	11.7	10.2	8.2	21.7	10.8
Minor Components (µg/g)							
Arsenic	75.0	100	101	115	100	90.3	220
Barium	677	893	697	796	576	500	213
Beryllium	3.39	4.69	2.94	5.01	3.39	2.72	2.09
Boron	70.8	158	137	196	142	129	63.1
Cadmium	40	50	39	54	40	47	15
Chromium	24	39	46	33	33	79	23
Cobalt	< 5	< 5	< 5	< 5	< 5	< 5	< 5
Copper	128	177	138	229	169	122	29.4
Lead	400	890	810	865	550	850	140
Lithium	53	66	60	69	62	56	30
Magnesium	2910	2930	2600	3370	3340	3730	9030
Manganese	413	348	305	407	442	383	635
Molybdenum	< 20	< 20	< 20	< 20	< 20	< 20	< 20
Nickel	91	107	91	122	101	89	47
Phosphorus	2320	2900	2040	3220	2510	1460	650
Potassium	8100	9000	6600	9900	8700	8500	5500
Rubidium	20	30	50	< 10	20	< 10	30
Silver	< 5	< 5	< 5	< 5	< 5	< 5	< 5
Strontium	246	303	221	339	259	185	60.1
Thorium	3.7	5.9	4.9	1.9	0.4	4.6	3.4
Titanium	2060	3090	1880	3670	2970	2080	1090
Uranium	7.3	10.0	10.0	7.4	22.6	8.1	1.2
Vanadium	244	325	264	405	321	282	37.5
Zinc	1390	1990	1890	2500	2200	3960	343
Zirconium	42	47	35	60	48	47	24

Run Number = Year Month Day Coal (E = Evans, D = Devco)

the previous study, this was confirmed by elemental sulphur analyses, which showed that the amount of sulphur present in elemental form in the samples was less than 1%. Similar results were obtained from the sulphide analyses. The lack of elemental sulphur in these samples suggests that either the combustion conditions which may have produced elemental sulphur did not exist when these wastes were generated, or that reactions occurred in the waste samples from the previous study which may have led to the production of elemental sulphur over time.

The main soluble sulphate is assumed to be $CaSO_4$. A small contribution may also have been made from other soluble sulphates, such as those of magnesium (Mg), sodium (Na) and potassium (K). Ferric sulphates are not likely to be present since the X-ray diffraction analyses showed that iron was mainly present as Fe_2O_3.

The amounts of silicon, iron, aluminum and carbon in the residues were generally highest in the cyclone materials, followed by the baghouse materials and then the bed materials. The carbon contents of the residues were determined through carbon dioxide and loss-on-ignition (LOI) analyses. The method used for CO_2 analysis includes loss of H_2S as well as that of CO_2. However, the measured sulphide contents of the residues were so low that the contribution of H_2S can be assumed to be negligible. The source of CO_2 was assumed to be $CaCO_3$. The CO_2 results were generally less than 3% and were only a small fraction of the LOI results for the cyclone and baghouse materials. This suggests that the relatively high LOI results for these samples may have been partially attributable to loss of water from silicates. It has been established that silicates such as kaolinite, montmorillonite and halloysite lose their hydroscopic and zeolitic water at temperatures from 100°C to 200°C; from 500°C to 750°C they lose their constitution water; and at about 1000°C they undergo a phase transition (Kato and Doi, 1967).

3.3 Exothermic Properties

The exothermic properties of the residues were examined using calorimeter tests to determine heats of reaction. Column tests were also attempted in order to determine temperature variations at different depths of residue within the column. The results of the calorimeter tests are given in Table 15. The heat of reaction or loss of enthalpy per unit mass of residue ($-\Delta H$) was determined from the equation:

$$-\Delta H = \frac{W(T_{max}-T_0)}{m} \qquad (1)$$

TABLE 15 CALORIMETER TESTS ON FRESH SAMPLES

Run Number	Liquid to Solid Ratio	Bed Material				Cyclone Material				Baghouse Material			
		ΔT_{30} (°C)	ΔT_{max} (°C)	t_{max} (min)	$-\Delta H$ (kJ/kg)	ΔT_{30} (°C)	ΔT_{max} (°C)	t_{max} (min)	$-\Delta H$ (kJ/kg)	ΔT_{30} (°C)	ΔT_{max} (°C)	t_{max} (min)	$-\Delta H$ (kJ/kg)
831115E	10:1	4.0	8.5	240	406	9.5	10.5	60	502	2.0	3.5	120	167
	5:1	8.0	15.5	180	370	20.0	20.0	30	478	2.5	6.0	180	143
	3:1	11.0	19.5	150	280	33.5	33.5	30	480	3.5	7.5	120	108
	Mean				352				487				139
831122E	10:1	3.5	3.5	30	167	5.0	7.0	90	335	0.5	0.5	30	24
	5:1	5.5	11.0	210	263	10.0	13.0	90	311	1.0	1.0	30	24
	3:1	7.0	16.5	180	237	17.0	21.0	60	301	2.0	3.0	60	43
	Mean				222				316				30
831124E	10:1	2.5	5.5	180	263	7.5	8.5	60	406	1.0	2.0	90	96
	5:1	5.0	9.0	150	215	14.5	15.5	60	370	2.0	3.0	90	72
	3:1	7.5	15.5	240	222	24.5	25.0	60	358	2.5	5.0	120	72
	Mean				233				378				80
831213E	10:1	8.0	9.5	90	454	7.0	7.5	60	358	1.0	2.0	90	96
	5:1	18.0	20.0	60	478	15.0	15.5	60	370	1.5	2.5	90	60
	3:1	33.0	33.0	30	473	25.5	25.5	30	366	2.0	2.5	60	36
	Mean				468				365				64
831214E	10:1	8.5	10.0	90	478	7.5	8.5	60	406	1.5	2.5	90	119
	5:1	17.0	19.5	60	466	15.5	16.5	60	394	4.0	5.5	90	131
	3:1	31.0	33.5	60	480	27.0	27.0	30	387	5.0	8.0	120	115
	Mean				475				396				122
840105E	10:1	8.5	10.0	120	478	3.0	4.5	120	215	1.5	1.5	30	72
	5:1	17.5	18.0	60	430	4.5	9.5	120	227	2.0	2.0	30	48
	3:1	30.5	31.0	60	444	7.0	14.5	120	208	3.0	3.5	60	50
	Mean				451				217				57
831124D	10:1	5.0	7.5	180	358					5.5	6.0	60	287
	5:1	9.0	13.5	210	323	NO SAMPLE AVAILABLE				11.0	12.0	60	287
	3:1	15.5	18.5	180	265					19.0	19.0	30	272
	Mean				315								282

Run Number = Year Month Day Coal (E = Evans, D = Devco)
ΔT_{30} = temperature increase after 30 minutes
ΔT_{max} = maximum temperature increase
t_{max} = elapsed time at which maximum temperature occurred
$-\Delta H$ = heat of reaction based on maximum temperature increase

where: W = the "equivalent in water" of the calorimeter (found to be equal to 2.86 kJ/K),

T_0 = initial temperature (K) - Kelvin,

T_{max} = maximum temperature (K),

m = mass of sample (kg), and

$-\Delta H$ is expressed in kJ/kg.

This equation has been modified from the one used in the previous study, where the temperature increase during the first 30 minutes was used instead of the maximum temperature increase. This change was made to take into account the large temperature increases that often took place in these residues after 30 minutes. This is illustrated in Table 15 by comparing the values of ΔT_{30} and ΔT_{max} and in Figure 2 from the graphs of temperature variation versus time for three sets of Queen's samples and the Summerside materials. In the previous study, little or no temperature increase occurred after 30 minutes.

The tests were conducted at liquid-to-solid ratios of 10:1, 5:1 and 3:1. Temperature increases were greatest at the 3:1 ratio, followed by the 5:1 and 10:1 ratios. This is as expected since less residue was available for heat release at the higher ratios.

The average maximum temperature increases at the 3:1 liquid-to-solid ratio were about 25°C in the Queen's bed and cyclone materials, 19°C in the Summerside bed and baghouse materials, and 5°C in the Queen's baghouse materials. These are higher than the maximum temperature increases of 3°C and 10°C measured in the two bed material samples in the previous study. The samples used in the previous study, however, had been in storage for two to three years prior to testing, and their measured exothermic properties may not have been representative of fresh samples. Since the samples used in this study were stored in sealed containers immediately after collection, and since the moisture contents of all samples were less than 1%, it was assumed that no significant exothermic reactions had occurred in the wastes prior to testing.

In general, maximum temperatures were reached in the bed materials after 2 to 4 hours, and in the cyclone and baghouse materials after 1 to 2 hours. Although distilled water was used in the calorimeter, the results of the leachability tests indicate that significant quantities of material may have dissolved in the water shortly after the start of the calorimeter tests. Baker and Jordan (1975) found that dissolved chlorides increased the rate of slaking of pure lime when present at concentrations of 1% (as sodium, magnesium and calcium salts) whereas dissolved sulphates and sulphites retarded

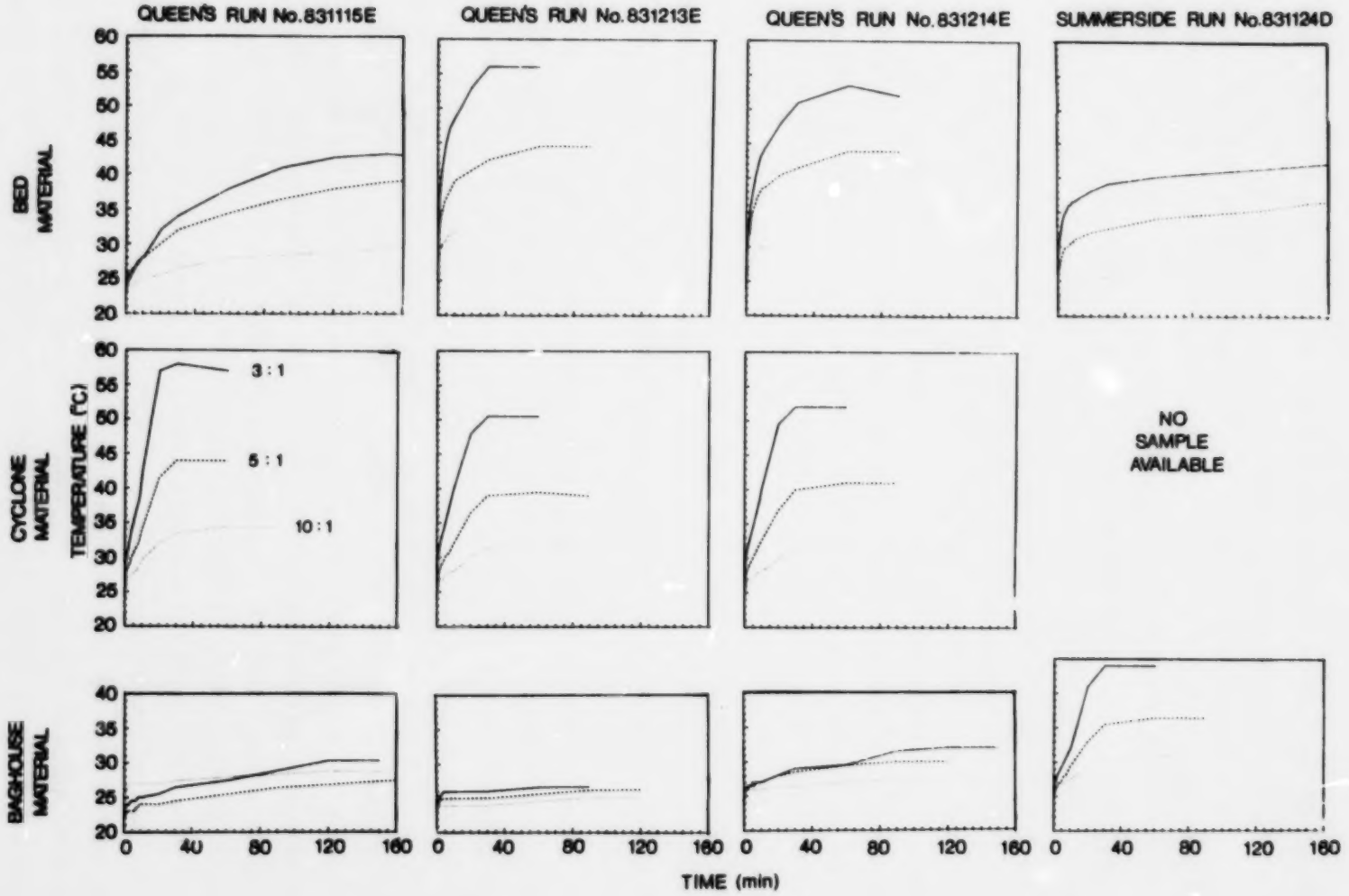


FIGURE 2 TEMPERATURE VARIATIONS IN THE CALORIMETER TESTS AT THREE LIQUID-TO-SOLID RATIOS

the rate of slaking. Since sulphate levels in the leachates were relatively high, this suggests that the slaking rates were retarded.

The average heats of reaction of the Queen's samples ranged from 222 to 475 kJ/kg for the bed materials, 217 to 487 kJ/kg for the cyclone materials, and 30 to 139 kJ/kg for the baghouse materials. The average heat of reaction of the Summerside bed material was 315 kJ/kg, which is within the range observed for the Queen's bed samples. However, the average heat of reaction of the Summerside baghouse material, at 282 kJ/kg, is 2 to 9 times greater than those of the Queen's baghouse samples.

Using the same approach employed with the preliminary acid neutralization capacity data, linear regression analyses were conducted to determine if any linear relationships existed between the heats of reaction of the Queen's residues and operating conditions and waste characteristics. Table 16 shows that the heats of reaction of the three types of residue were linearly related to their calcium and calcium oxide content and their acid neutralization capacities, and that the heat of reaction of the bed material was also linearly related to its sulphur content. These relationships are plotted in Figures 3 to 6. Although the regression analyses were only conducted on data from the Queen's residues, the corresponding points for the Summerside bed and baghouse materials also show good agreement with the regression lines, suggesting that the relationship may be applicable for wastes from different AFBC units.

The literature review and results of the previous study, and the linear regression results plotted in Figure 5, indicate that the exothermic nature of these residues appears to be at least partially attributable to the presence of unslaked calcium oxide (also known as quicklime or unslaked lime). Further evidence of this is presented in Figure 7, where the ratios of the heats of reaction of all fresh samples in this study (i.e., Queen's and Summerside) to the heat of reaction of pure lime (1140 kJ/kg) are plotted versus the calcium oxide content of the residues. Also shown is the relationship that would exist if the observed heats of reaction were due entirely to lime. While many of the points lie below this line, the graph indicates that most of the observed heat of reaction can be accounted for by the hydration of lime.

The linear regression analyses indicate a very strong relationship between heat of reaction and acid neutralization capacity. Although not shown in Figure 6, the points for the Summerside bed and baghouse materials also fall on the regression lines. Furthermore, although the linear regressions for acid neutralization capacity were conducted independently on each type of residue, the results shown in Figure 6 suggest that a single regression line for all three residue types may be appropriate. Since acid

TABLE 16 LINEAR REGRESSION ANALYSES ON HEATS OF REACTION OF FRESH QUEEN'S SAMPLES

Linear Equation Evaluated: Heat of Reaction (kJ/kg) = A + B x Variable Value

Residues from Queen's AFBC Unit (Fresh Samples)	Coefficients	Variables: Operating Conditions: Ca/S Ratio	Operating Conditions: Bed Temperature (°C)	Operating Conditions: % Excess Air	Operating Conditions: Cyclone Recycle Fraction	Waste Characteristics: Calcium Content (%)	Waste Characteristics: Total Sulphur Content (%)	Waste Characteristics: CaO Content (%)	Waste Characteristics: Acid Neutralization Capacity (g-equiv.kg)
Bed Ash	A	N.S.	N.S.	N.S.	N.S.	-732.	936.	-141.	-177.
	B					25.1	-52.6	12.5	34.7
	r^2					0.91	0.94	0.97	0.99
Cyclone Material	A	N.S.	N.S.	N.S.	N.S.	-169.	N.S.	-36.2	-8.82
	B					15.0		11.9	24.6
	r^2					0.98		0.97	0.93
Baghouse Material	A	N.S.	N.S.	N.S.	N.S.	-60.0	N.S.	-17.0	-21.1
	B					10.2		10.1	22.9
	r^2					0.91		0.93	0.84

Note: N.S. = not significant at 95% confidence level
r^2 = coefficient of determination = explained variance/total variance

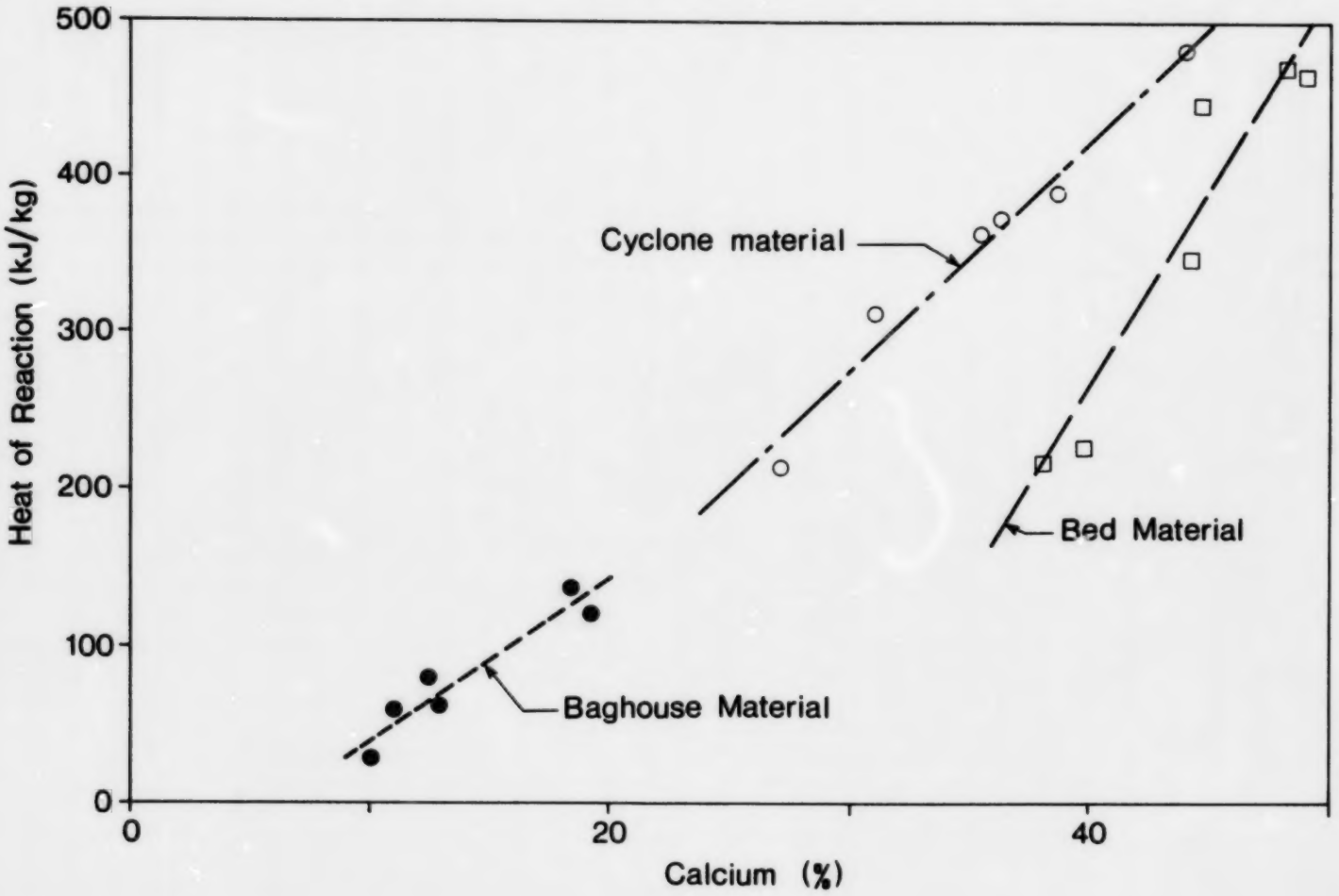


FIGURE 3 LINEAR CORRELATIONS BETWEEN HEAT OF REACTION AND CALCIUM CONTENT OF QUEEN'S FRESH SAMPLES

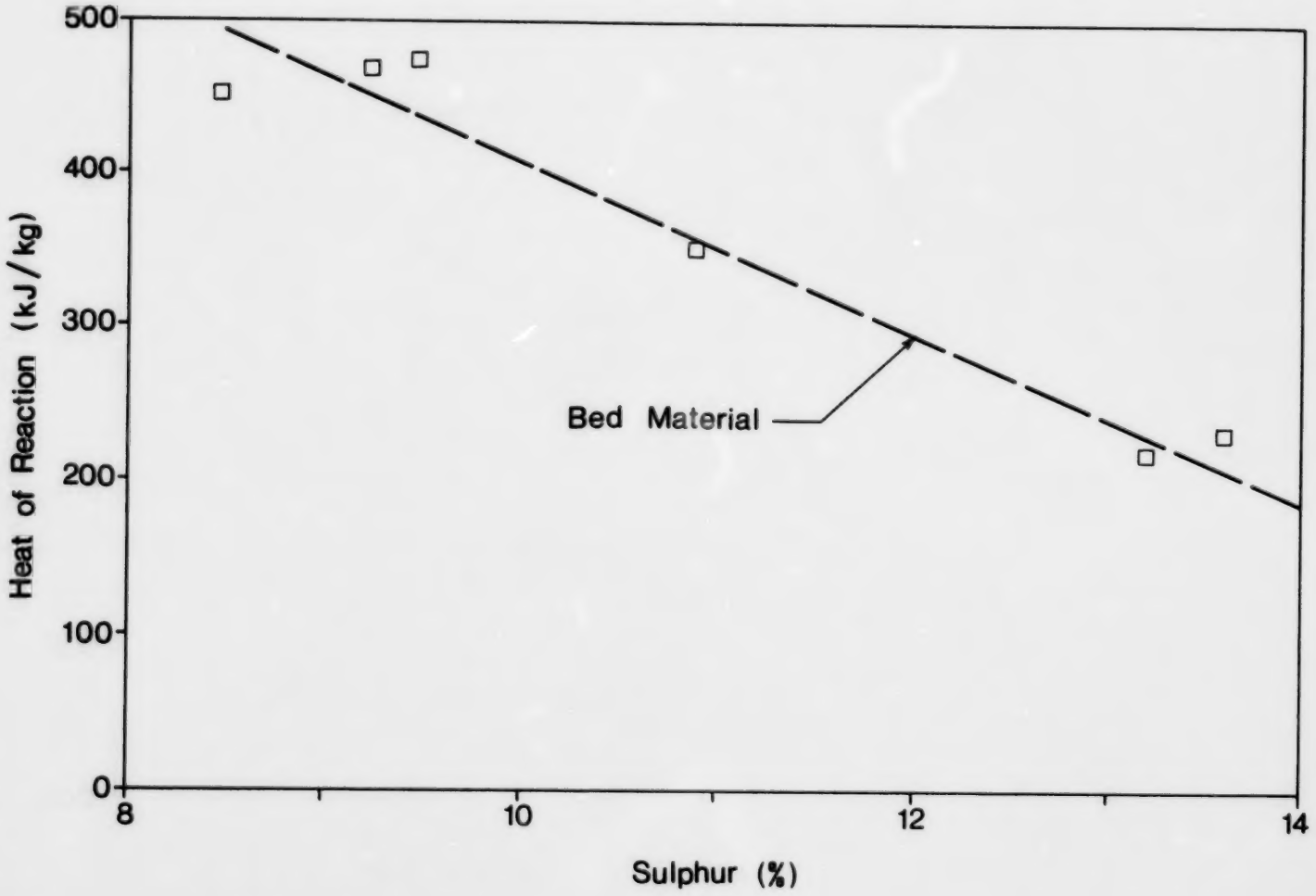


FIGURE 4 LINEAR CORRELATION BETWEEN HEAT OF REACTION AND SULPHUR CONTENT OF QUEEN'S FRESH BED MATERIAL SAMPLES

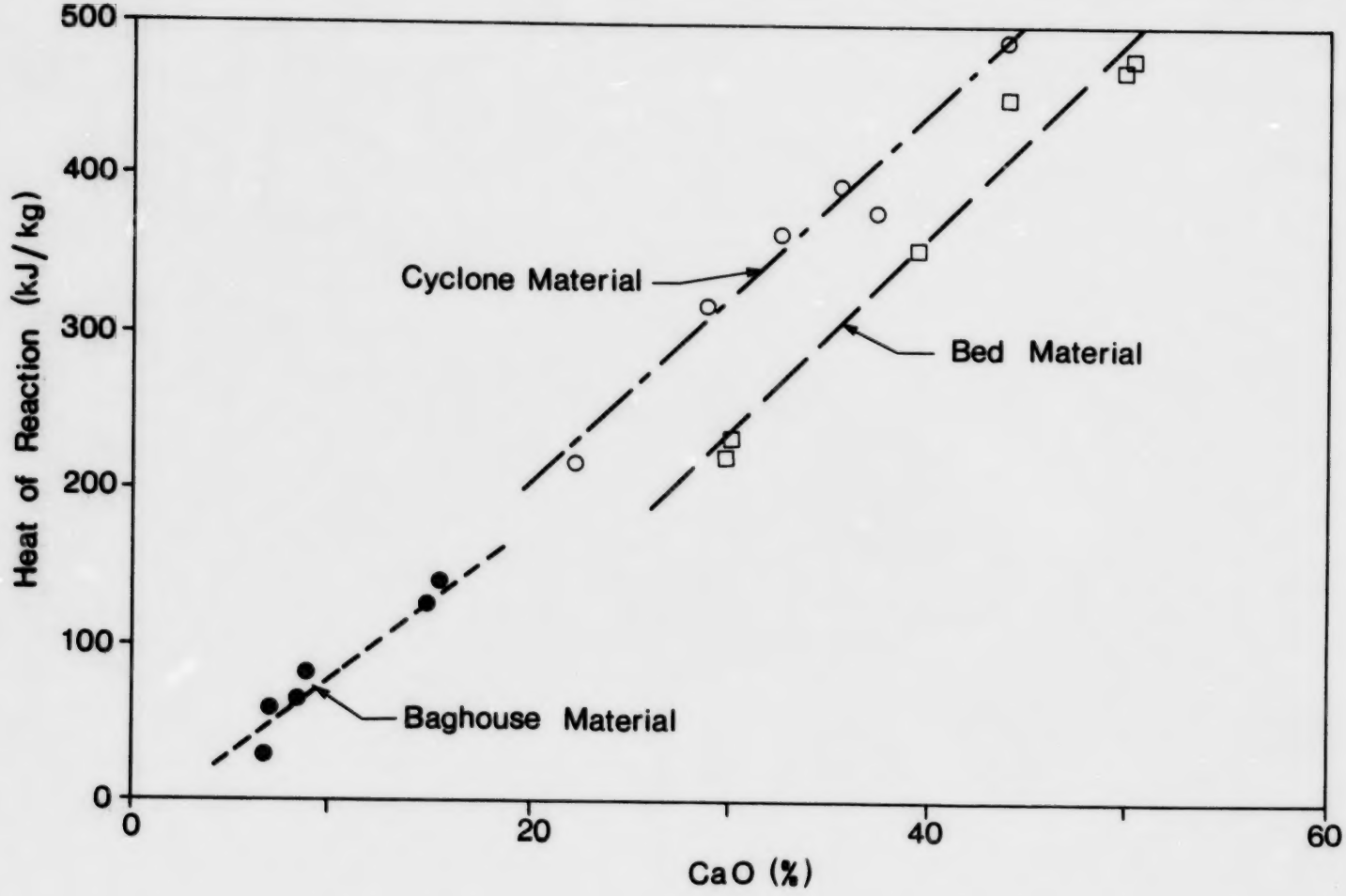


FIGURE 5 LINEAR CORRELATIONS BETWEEN HEAT OF REACTION AND CALCIUM OXIDE CONTENT OF QUEEN'S FRESH SAMPLES

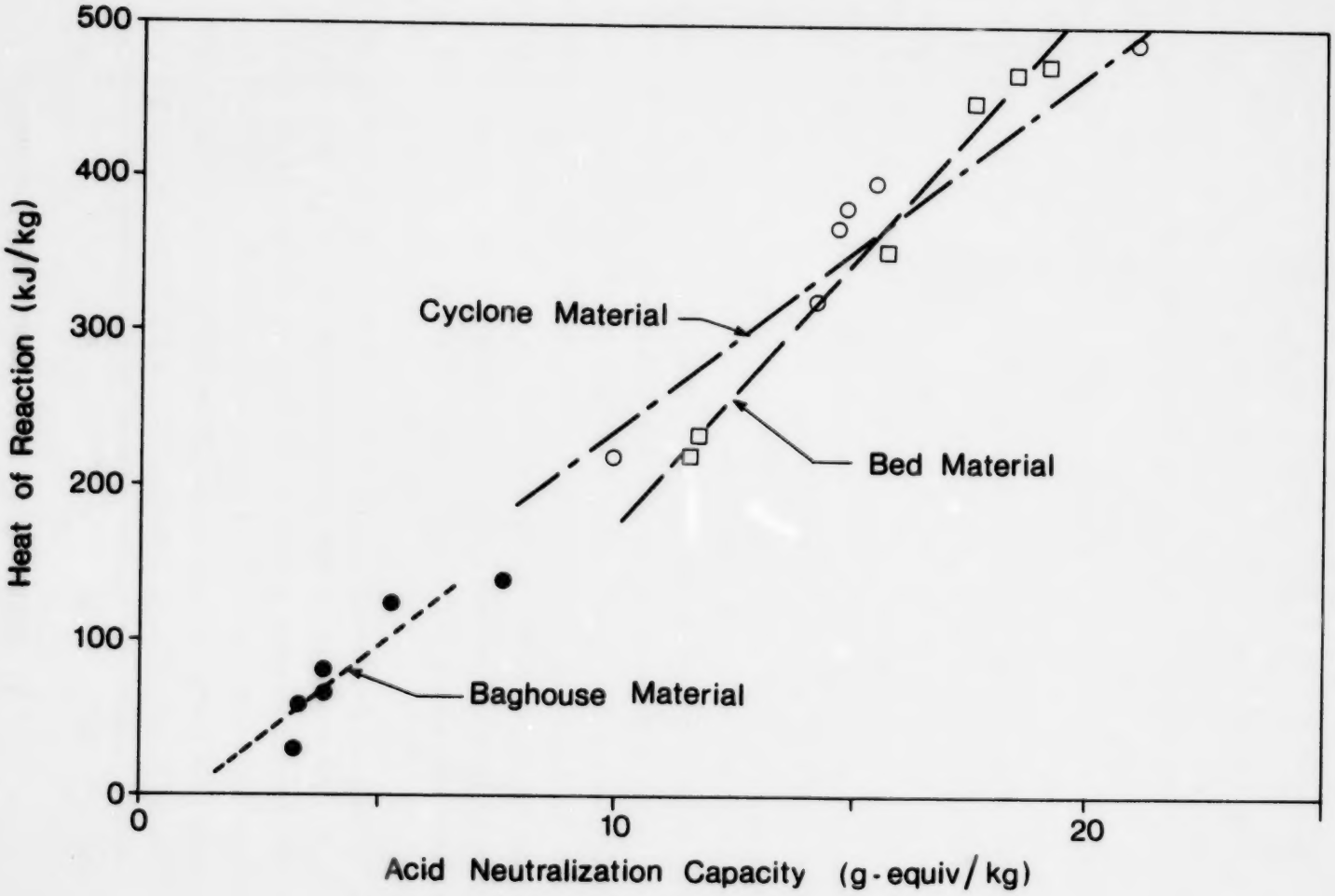


FIGURE 6 LINEAR CORRELATIONS BETWEEN HEAT OF REACTION AND ACID NEUTRALIZATION CAPACITY OF QUEEN'S FRESH SAMPLES

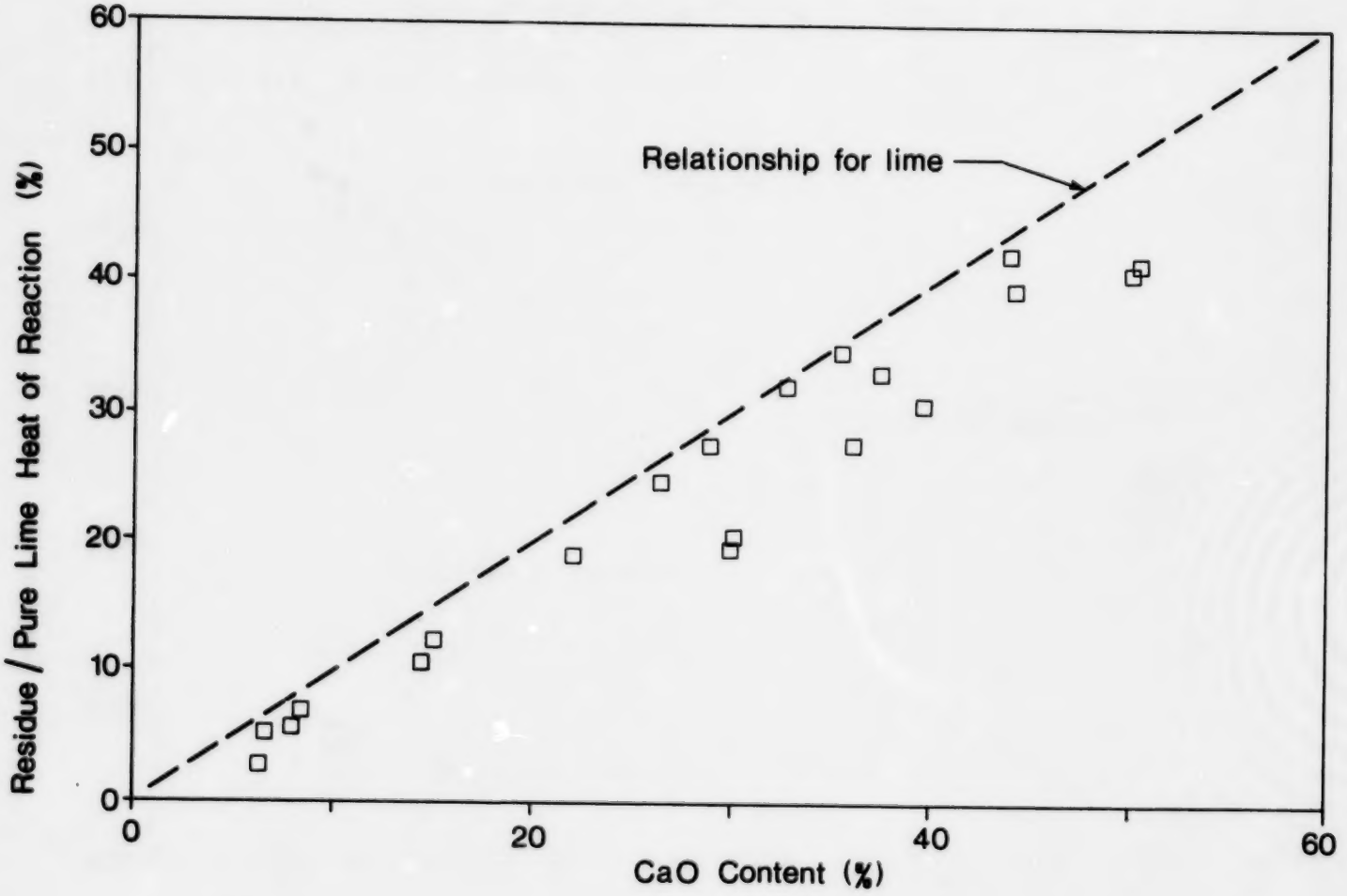


FIGURE 7 RATIO OF HEAT OF REACTION OF RESIDUES TO HEAT OF REACTION OF PURE LIME VERSUS CALCIUM OXIDE CONTENT OF RESIDUES

neutralization capacity determinations are much easier and faster than calorimeter testing, the possible usefulness of acid neutralization capacity as a predictor of the heat of reaction of these types of AFBC residues should be given further consideration.

A complete test run using the column exothermic apparatus was not achieved during the study because of problems encountered during the tests which necessitated modifications to the test equipment. These problems arose because of pressure created inside the column when the residues were hydrated. This pressure was probably largely due to residue expansion, but may have also been due to heat and steam generation. The pressure bent the thermocouples and the wire screen on the bottom of the column downward as much as 1 cm during some initial runs. The thermocouples had to be modified three times, each time with a stronger outer sheathing, before they were able to survive a test without having to be replaced because of excessive deformation. The final design made use of 0.9 mm thick 316 stainless steel which was formed into a 6 mm outer diameter tube which enclosed each thermocouple. The wire screen trap welded into the base ring of the column also had to be replaced when it was damaged (i.e., deformed downward) beyond repair during the first set of tests. It was replaced with a circular 1.6 mm thick stainless steel plate which was drilled on 6.4 mm centres with 3.2 mm holes. The pressures created within the column and possible pozzolanic reactions compacted and solidified the residues so that the residue and thermocouples were difficult to remove after each run. The material had to be removed from the column using a power hand drill with a masonry bit. Since the tested materials expanded and solidified under confined conditions, their leachability under field disposal conditions may be considerably less than that indicated by the batch leaching tests (Section 3.4). Further testing of the modified exothermic column will be conducted in a subsequent AFBC residue characterization study.

During some of the incomplete trial runs with Queen's bed material from Run 831213E, temperatures of 160°C to 170°C were measured within the column. These high temperatures and the problems encountered due to the high pressure created within the column support the findings of the previous study, which showed that rapid and violent thermal reactions could occur when some AFBC wastes come in contact with water. The possibility of such reactions occurring in a field disposal situation should be taken into consideration during the development of handling, storage and disposal guidelines for AFBC residues.

3.4 Leaching Properties

Serial batch leaching tests were conducted in order to characterize the leachability of the AFBC solid residues. The principle advantage of this approach is that it requires only a fraction of the time needed to conduct a column leaching test. Column leaching tests are generally accepted to be more representative of leachability under field disposal conditions than batch leaching tests; however, insufficient time was available to conduct column leaching tests in this and the previous study. The major differences between column and batch leaching tests are the configuration of the waste (i.e., compacted within a column versus suspended within a leaching medium) and the method of contacting the waste with the leaching medium (i.e., slow percolation through a column open to the atmosphere versus continuous mixing within a sealed container). These differences could have significant effects on leachability, particularly in light of the column exothermic test results, which indicate that some AFBC residues solidify under confined conditions. The following results must, therefore, be interpreted with these differences in mind. Column leaching tests will be conducted in a subsequent AFBC residue characterization study.

The results of the tests are given in Appendix A (Tables A.1 to A.20). Included are the concentrations of the measured parameters in the solids both before and after leaching, in the leachates after Cycles 1, 2, 5, 10 and 20, and in a blank of deionized water which was submitted to the laboratories for quality control.

The pH, conductivity and TDS concentrations of the leachates were measured after every cycle (Tables A.21 to A.27). Also included in these tables are the initial and final dry weights of the leached samples, and the percent weight loss of the residues during the 20 leaching cycles. The data in Table A.21 to A.27 for the first and last leaching cycles and for percent weight loss are summarized in Table 17.

The pH of leachates from all residues decreased during the tests from about 12.5 in Cycle 1 to about 11.0 in Cycle 20. In general, leachate conductivities and TDS concentrations in Cycle 1 were approximately 9.0 mS/cm and 5000 mg/L, and decreased by about 95% during the 20 cycles. However, there were some notable exceptions. For example, for two Queen's bed materials (Runs 831213E and 831214E), conductivities decreased by only 37% and 19%, and TDS concentrations decreased by only 70% and 61%. Similarly, conductivity and TDS for the Queen's cyclone material from Run 831115E decreased by only 48% and 76% over the 20 cycles. The reasons for these differences are not apparent.

TABLE 17 SUMMARY OF RESULTS OF 20 CYCLE LEACHING TESTS WITH DEIONIZED WATER

Material	Run No.	pH		Conductivity (μS/cm)		TDS (mg/L)		Percent Weight Loss
		Cycle 1	Cycle 20	Cycle 1	Cycle 20	Cycle 1	Cycle 20	
Queen's Bed	831115E	12.4	11.1	9000	582	4866	228	76.7
	831122E	12.4	10.8	9030	520	4492	180	79.1
	831124E	12.4	10.9	8980	450	4560	174	81.4
	831213E	12.4	12.2	8900	5600	4432	1328	81.4
	831214E	12.5	12.4	8840	7200	4400	1730	81.4
	840105E	12.6	11.9	8990	2130	4506	516	76.7
	Mean	12.5	11.6	8957	2747	4543	693	79.5
Queen's Cyclone	831115E	12.4	12.1	9160	4800	4910	1198	53.5
	831122E	12.5	10.9	9290	370	4878	132	48.8
	831124E	12.4	11.1	9200	577	4808	212	60.5
	831213E	12.5	11.1	9150	544	4782	196	58.1
	831214E	12.6	11.2	9110	700	4786	228	65.1
	840105E	12.7	10.8	9240	340	4686	124	48.8
	Mean	12.5	11.2	9192	1222	4808	348	55.8
Queen's Baghouse	831115E	12.4	10.9	10820	510	5548	206	13.9
	831122E	11.9	10.4	6580	310	4476	148	20.9
	831124E	12.5	10.3	11390	294	5358	120	20.9
	831213E	12.4	10.5	11170	325	5514	132	23.3
	831214E	12.5	10.8	10490	420	5460	170	30.2
	840105E	13.4	10.6	10770	250	5258	124	23.3
	Mean	12.5	10.6	10203	352	5269	150	22.1
Summerside: Bed	831124D	12.6	11.1	8990	570	4476	212	76.7
Baghouse	831124D	12.6	11.1	9150	450	4734	174	44.2

Run Number = Year Month Day Coal (E = Evans, D = Devco)

Conductivities in leachates from the bed and cyclone materials generally remained relatively constant or decreased slightly during the first 10 to 15 cycles, then decreased rapidly. On the other hand, conductivities in leachates from the baghouse materials, with the exception of the Summerside material, decreased rapidly after Cycle 1. Conductivities in the Summerside baghouse leachates decreased slowly from 9.2 to 7.0 mS/cm during the first 10 cycles, then decreased more rapidly during subsequent cycles to reach 0.45 mS/cm at Cycle 20.

Generally, TDS concentrations in leachates remained relatively constant or decreased slightly during the first 7 to 10 cycles for the bed materials, and during the first 4 cycles for the cyclone materials, then decreased rapidly. TDS concentrations in leachates from the baghouse materials, again with the exception of the Summerside material, decreased steadily throughout the 20 cycles. TDS concentrations in the Summerside baghouse leachates decreased slowly during the first 4 cycles from 4700 to 4200 mg/L, then decreased rapidly during subsequent cycles to reach 174 mg/L at Cycle 20.

The amount of solid material lost during a leaching test was determined by weighing the residue remaining at the end of the test. This may overestimate the actual weight loss due to leaching as it does not take into account losses by other means such as the retention of solids on filter papers.

The weight loss of solid material during the 20 leaching cycles ranged between 14% and 81%, and was strongly dependent on the type of residue (Table 17). All bed materials had an average weight loss of about 80%. The Queen's cyclone and baghouse materials had average losses of about 56% and 22%, respectively, whereas the weight loss from the Summerside baghouse material was 44%. The relatively high solubility of these residues compared to conventional PCF ashes probably arises from the high calcium oxide and calcium sulphate content of the AFBC residues, which are more readily dissolved that the silicates in the PCF residues, and from the lower combustion temperatures used in AFBC systems, which results in non-vitrified solids residues that are more leachable than PCF ashes.

The general trends in weight loss during the leaching tests are shown in Figure 8. These graphs were produced from the TDS data given in Tables A.21 to A.27, and show the normalized percent cumulative weight loss over the 20 leaching cycles (i.e., the cumulative total weight loss for each test is 100 percent). Normalizing the weight loss in this manner clearly indicates how each residue behaved differently during the tests. The portions of the graph that are linear indicate that the mass of sample being

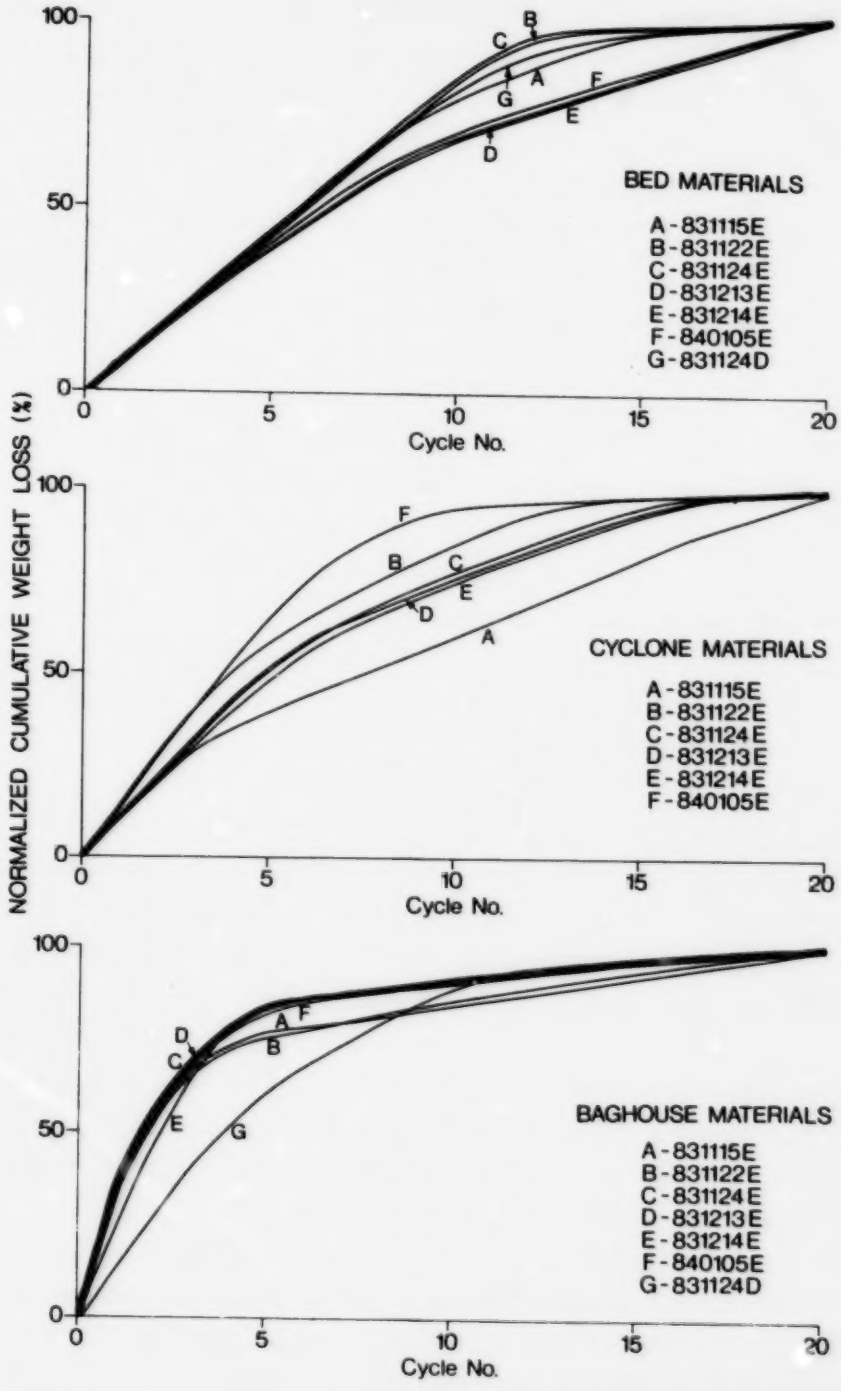


FIGURE 8 **NORMALIZED CUMULATIVE WEIGHT LOSS DURING LEACHING TESTS**

dissolved during each cycle was equal. The portions of the graph that are asymptotic to 100% indicate that very little mass was being dissolved within the corresponding leaching cycles. Figure 8 shows that most leaching of the baghouse materials took place during the first five cycles, whereas most bed and cyclone materials continued to leach at a relatively steady rate up to and sometimes beyond the tenth cycle.

The concentrations of the measured parameters in the leachates from Cycles 1, 2, 5, 10 and 20 are given in Tables A.1 to A.20. The maximum concentrations observed in all leachates are summarized in Table 18. Only a few elements were leached because of the relative insolubility of most elements under alkaline conditions. The main constituents in the leachates were calcium and sulphate, with minor amounts of chloride, sodium, potassium, fluoride, silicon, aluminum and strontium. The concentrations of most constituents decreased with increasing leaching cycles. The major exceptions were aluminum, boron and vanadium. These elements usually increased in concentration during later cycles, particularly in leachates from the cyclone and baghouse materials.

Typically, calcium and sulphate concentrations were several orders of magnitude greater than the other leached elements. Figures 9 and 10 show changes in calcium and sulphate concentrations in the leachates from the Queen's residues. In general, concentrations decreased with increasing leaching cycles. There were some exceptions to this trend, for example, sulphate concentrations in leachates from Run 831122E bed material increased from 1320 to 1820 mg/L between Cycles 2 and 10, before decreasing to 38 mg/L at Cycle 20. Since leachates from all cycles were not analyzed, it is possible that sulphate concentrations continued to increase past Cycle 10 before peaking, or that the peak occurred between Cycles 5 and 10. In general, the greatest decreases in sulphate concentrations were observed in the leachates from the baghouse materials followed by the cyclone and bed materials.

A white precipitate was observed in some of the leachate samples following an extended standing period, suggesting that the leachates were initially supersaturated. Subsequent X-ray analyses revealed that the precipitate was composed of $CaSO_4$, probably present in a hydrated form, with lesser amounts of $Ca(OH)_2$.

In order to further evaluate the results of the leaching tests, the use of chemical speciation models was considered. Following a brief literature review, two types of models were selected for further study. GEOCHEM (Sposito and Mattigod, 1979) and its reduced version MINEQL (Westall et al., 1976) were the first models evaluated. They were primarily developed to study soil chemistry reactions. The second type of model evaluated was PHREEQE (Parkhurst et al., 1980), which was designed to model

TABLE 18 MAXIMUM CONCENTRATIONS REACHED IN AFBC RESIDUE LEACHATES

Element	Queen's			Summerside	
	Bed	Cyclone	Baghouse	Bed	Baghouse
Aluminum	3.99	4.48	6.94	4.16	4.17
Arsenic	< 0.005	0.024	0.035	< 0.005	0.027
Barium	0.049	0.437	1.03	< 0.005	0.295
Beryllium	< 0.0005	< 0.0005	< 0.0005	< 0.0005	< 0.0005
Boron	0.071	0.188	0.314	0.041	0.066
Cadmium	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01
Calcium	1490	1570	1790	1450	1440
Chloride	20.4	118	679	12.2	36.6
Chromium	0.01	< 0.01	< 0.01	< 0.01	< 0.01
Cobalt	0.06	< 0.05	< 0.05	< 0.05	< 0.05
Copper	0.018	0.018	0.029	0.018	< 0.009
Fluoride	1.0	15.6	5.6	1.3	1.9
Iron	0.13	0.15	0.30	0.13	0.13
Lead	< 0.05	0.25	5.21	< 0.05	< 0.05
Magnesium	0.10	0.13	0.26	0.03	0.02
Manganese	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01
Molybdenum	0.4	0.4	0.8	0.4	0.3
Nickel	0.08	0.08	0.08	0.07	0.07
Phosphorus	0.6	< 0.6	0.6	< 0.6	< 0.6
Potassium	3	4	47	2	3
Silicon	8.42	7.57	10.6	4.04	3.56
Silver	0.015	0.014	0.011	0.007	0.011
Sodium	2	8	113	< 1	2
Strontium	1.58	4.50	2.39	1.15	1.21
Sulphate	1820	1544	1792	1413	1320
Thorium	< 0.003	< 0.003	< 0.003	< 0.003	< 0.003
Titanium	< 0.005	< 0.005	< 0.005	< 0.005	< 0.005
Uranium	0.0074	0.0036	0.0043	0.0016	0.0048
Vanadium	0.018	0.060	0.326	< 0.005	0.028
Zinc	0.13	0.47	1.89	0.08	< 0.05
Zirconium	< 0.05	< 0.05	< 0.05	< 0.05	< 0.05

units are mg/L

groundwater chemistry reactions. This model was able to predict the supersaturation of the leachates with $CaSO_4$ under the conditions of the leaching protocol. The use of models such as these appears to show promise for the evaluation of AFBC solid residues under leaching conditions which may not be easily controlled in a laboratory environment.

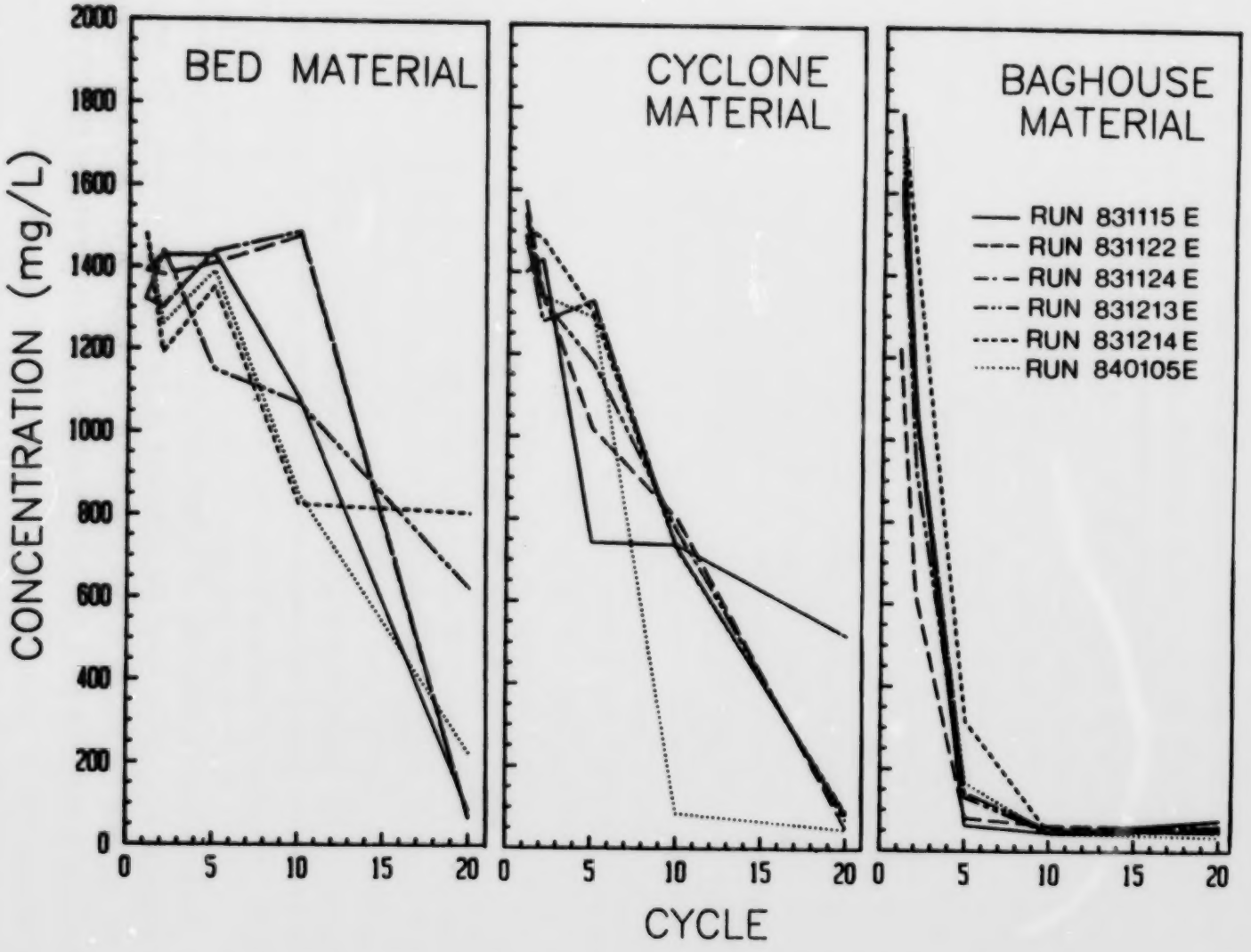


FIGURE 9 CALCIUM CONCENTRATIONS IN QUEEN'S FRESH SAMPLE LEACHATES DURING 20 CYCLE LEACHING TESTS

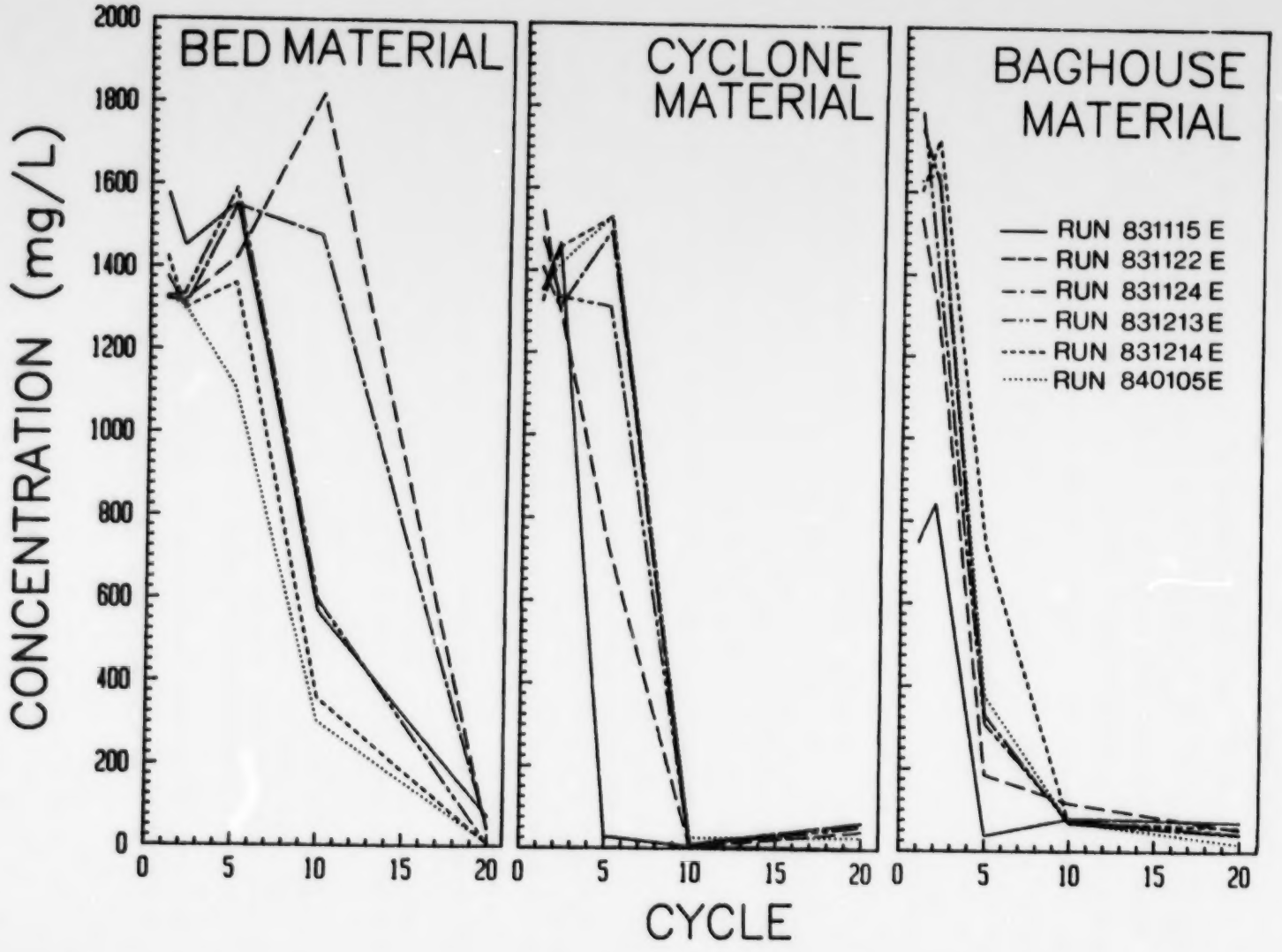


FIGURE 10 SULPHATE CONCENTRATIONS IN QUEEN'S FRESH SAMPLE LEACHATES DURING 20 CYCLE LEACHING TESTS

3.5 Quality Control

Table B.1 in Appendix B presents the comparative analysis of the standard reference material as certified by the U.S. National Bureau of Standards and the results of analyses by the methods used during this study, including inductively coupled argon plasma spectroscopy, atomic adsorption spectroscopy and neutron activation analysis. This comparison shows that concentrations of elements in the reference material were quantified with reasonable accuracy. The ratio of measured values to certified values was between 91% and 107%, with the exceptions of lead (83%) and sodium (117%).

The results of replicate analyses performed on five solid residues, both before and after leaching, and on leachates from these residues, are given in Tables B.2 to B.4. These data indicate that the analytical results were reproducible.

The results of the quality assurance program using spiked leachate samples are presented in Table B.5. Overall, the recoveries of the spiked additions were acceptable, particularly in light of the high TDS concentrations in the spiked leachates. All recoveries ranged between 80% and 116%, with the exceptions of one spike for chromium (60%) and one for potassium (50%). However, these low recoveries were obtained in samples that had been spiked at levels only slightly above their detection limits.

The calcium and total sulphur contents of the fresh samples were determined using a variety of analytical techniques. The results of these analyses are compared in Tables B.6 and B.7. Overall, there was very good agreement among all methods except for the sulphur determinations by atomic absorption, which were consistently higher than those of the other two methods.

CONCLUSIONS AND RECOMMENDATIONS

1. AFBC residues from units burning high sulphur (e.g., 4% to 8%) coals in limestone beds at high calcium-to-sulphur ratios appear to have properties that are unique in comparison to conventional PCF combustion residues. They may, therefore, require different collection, handling, transportation and/or disposal techniques than those recommended for conventional coal-fuelled power plant wastes.

2. The residues are exothermic when hydrated. To prevent thermal damage to landfill liners, the residues may have to be slaked prior to disposal. This may require the addition of large amounts of water in excess of slaking requirements in order to prevent the large temperature increases experienced at low liquid-to-solid ratios. Problems encountered during the water holding capacity tests with wetting two of the baghouse materials suggest that some AFBC residues may be difficult to slake, and that the conventional methods of dust suppression used at PCF ash disposal sites may not work satisfactorily at AFBC dispos areas.

3. The major cause of exothermicity appears to be the presence of unslaked calcium oxide. By convention, calcium content in coal combustion wastes is often reported as 'CaO', however, this may be very misleading since calcium oxide may be present in only small amounts in PCF residues but can be a major component of some AFBC residues. This makes it difficult to compare the results of calcium analyses on different coal combustion residues that have been reported using this convention, especially if the exothermic properties of the residues are of interest.

4. The residues expand considerably when hydrated. This should be taken into account in determining volume requirements for disposal areas. A method for measuring this expansion should be developed. Studies should be made to determine whether the water in the slaked materials is retained interstitially or incorporated into the crystalline structure, and to examine if the wastes can be returned to their preslaked volume by compaction.

5. Batch leaching tests conducted on the residues showed that they are highly soluble in water. However, the results of column exothermic testing indicate that the residues may solidify when hydrated in a confined area, which is likely to significantly decrease their leachability. This should be examined by conducting column leaching tests on the residues.

6. The results of the batch leaching tests suggest that drainage from slaking operations and leachates from landfilled wastes will be highly alkaline with high TDS concentrations, and will need to be collected and treated before they are discharged. Methods for treating these effluents should be assessed.

7. Results of a preliminary investigation of computerized chemical speciation models indicate that these programs are able to favorably predict leachate chemistries. Further investigations using this approach should be conducted.

REFERENCES

ASTM, Annual Book of ASTM Standards, American Society for Testing and Materials, Philadelphia, PA (1982).

Baker, R.J. and R.W. Jordan, "Effect of Dissolved Solids in SO_2 Scrubber Water Used For Lime Slaking", Proceedings of the Third WWEMA Industrial Pollution Conference, Chicago, IL (April, 1975).

Becker, H.A. and R.K. Code, The Pilot Plant Installation at Queen's University for Studies of Atmospheric Fluidized Bed Combustion, Report QFBC.TR.82.1, Queen's Fluidized Bed Combustion Laboratory, Dept. of Chemical Engineering, Queen's University, Kingston, Ontario (1982).

Becker, H.A. and R.K. Code, Pilot Scale Trials on Atmospheric Fluidized Bed Combustion of High-Sulphur Eastern Canadian Coals (Minto and Devco) with Limestone Addition for Sulphur Capture, Technical Report QFBC.TR.83.1, Queen's Fluidized Bed Combustion Laboratory, Dept. of Chemical Engineering, Queen's University, Kingston, Ontario (1983).

Becker, H.A., R.K. Code, R.W. McCleave and J.R. Stephenson, 1983-84 Atmospheric Fluidized Bed Combustion (AFBC) Waste Sample and Information Collection Program, Report QFBC.TR.84.2, Queen's Fluidized Bed Combustion Laboratory, Dept. of Chemical Engineering, Queen's University, Kingston, Ontario (1984).

CH2M Hill Canada Ltd., Characteristics of Coal-Fuelled Fluidized Bed Combustion Wastes, DSS Contract No. 5ISS.KE145-1-0739 for Environment Canada (March, 1982).

Collins, R.J., "Utilization of Fluidized Bed Combustion Wastes", Journal of Testing and Evaluation 8(5):259 (Sept., 1980).

Côté, P.L. and T.W. Constable, "Development of a Canadian Data Base on Waste Leachability", Hazardous and Industrial Solid Waste Testing: Second Symposium, ASTM STP 805, R.A. Conway and W.P. Gulledge (eds), American Society for Testing and Materials (1983).

Environmental Protection Service, A Preliminary Evaluation of the Physical, Chemical and Leaching Properties of AFBC Solid Wastes, 1982/83, Environment Canada Report No. EPS 3/PG/2 (1985).

Environmental Protection Service, Pollution Control Implications of Fluidized Bed Technology for Coal-fired Steam Electric Power Generation, CH2M Hill Canada Ltd., Environment Canada Report No. EPS 3-WP-82-2 (1982).

Furman, N.H. (editor), Standard Methods of Chemical Analysis, 6th edition, Vol. 1 (1962).

Kato, C. and A. Doi,, "Dehydration of Clay Minerals Under N_2 Reduced Pressure by Differential Thermal Analysis", Kogyo Kagaku Zasshi, 69(9):1686 (1966) (Japan), Chem. Abstr. 67, 111, 122u (1967).

Parkhurst, D.L., D.C. Thorstenson and L.N. Plummer, PHREEQE - A Computer Program for Geochemical Calculations, U.S. Geological Survey, Report No. USGS/WRI-80-96 (November, 1980).

Sposito, G. and S.V. Mattigod, GEOCHEM: A Computer Program for the Calculation of Chemical Equilibria in Soil Solutions and Other Natural Water Systems, Dept. of Soil and Environmental Sciences, University of California, Riverside, California (1979).

Stone, R. and R.L. Kahle, Environmental Assessment of Solid Residues from Fluidized Bed Fuel Processing, Final Report, EPA 600/7-78-107 (June, 1978).

Taylor, M.E.D. and F.D Friedrich, The CFB Summerside Project: Canadian State-of-the-Art in AFBC Boilers, CANMET, Energy Research Program, Division Report ERP/ERL 82-10(TR) (April, 1982).

Westall, J.C., J.L. Zachary and F.M.M. Morel, MINEQL - A Computer Program for the Calculation of Chemical Equilibrium Composition of Aqueous Systems, Water Quality Laboratory, Dept. of Civil Engineering, Massachusetts Institute of Technology, Technical Note 18 (July, 1976).

APPENDIX A
LEACHING TEST RESULTS

TABLE A.1 CHARACTERIZATION OF QUEEN'S BED MATERIAL (831115E) AND LEACHATES

Parameter	Solids (mg/kg)		Leachates (mg/L)					
	Before Leaching	After Leaching	Cycle 1	Cycle 2	Cycle 5	Cycle 10	Cycle 20	Blank
Aluminum	4 960	22 600	< .01	< .01	< .01	< .01	3.99	< .01
Arsenic	29.0	174	< .005	< .005	< .005	< .005	< .005	< .005
Barium	81.0	205	.036	< .005	< .005	< .005	< .005	< .005
Beryllium	< .05	1.00	< .0005	< .0005	< .0005	< .0005	< .0005	< .0005
Boron	22.4	121	.047	.033	.028	.025	.016	< .004
Cadmium	< 1	< 1	< .01	< .01	< .01	< .01	< .01	< .01
Calcium	454 000	284 000	1 390	1 430	1 430	1 080	85.2	< .01
Chloride	-	-	20.4	17.3	9.5	1.9	2.9	< .1
Chromium	2	38	< .01	< .01	< .01	< .01	< .01	< .01
Cobalt	< 5	< 5	< .05	< .05	< .05	< .05	< .05	< .05
Copper	8.7	32.4	.018	0.13	0.10	.010	< .009	< .009
Fluoride	-	-	< .1	< .1	< .1	< .1	1.0	< .1
Iron	17 600	76 200	0.13	.11	.07	.07	.02	< .01
Lead	< 5	20	< .05	< .05	< .05	< .05	< .05	< .05
Lithium	5	8	-	-	-	-	-	< .01
Magnesium	3 270	15 200	< .01	< .01	< .01	< .01	.03	< .01
Manganese	500	2 390	< .01	< .01	< .01	< .01	< .01	< .01
Molybdenum	< 20	< 20	.3	< .2	< .2	< .2	< .2	< .2
Nickel	27	34	.06	.07	.06	.06	< .05	< .05
Phosphorus	350	2 090	< .6	< .6	< .6	< .6	< .6	< .6
Potassium	900	1 700	3	< 1	< 1	2	< 1	<1
Silicon	12 800	63 900	< .05	< .05	< .05	< .05	4.40	< .05
Silver	< 5	< 5	< .005	< .005	< .005	< .005	< .005	< .005
Sodium	1 100	1 600	< 1	< 1	< 1	< 1	< 1	<1
Strontium	36.7	102	1.19	.563	.289	< .001	.053	< .001
Sulphate	-	-	1 576	1 451	1 555	567	71	<1
Thorium	1.0	-	< .003	< .003	< .003	< .003	< .003	< .003
Titanium	365	1 880	< .005	< .005	< .005	< .005	< .005	< .005
Uranium	2.8	-	.0074	< .001	.0015	.0010	.0011	< .001
Vanadium	19.4	170	< .005	< .005	< .005	< .005	< .005	< .005
Zinc	189	280	.06	.09	.07	.07	< .05	< .05
Zirconium	15	55	< .05	< .05	< .05	< .05	< .05	< .05
Acidity	-	-	< 1	< 1	< 1	< 1	< 1	<1
Hardness	-	-	3 475	3 575	3 575	2 700	213	<1
pH (units)	-	-	12.4	12.4	12.3	12.4	11.1	7.2
TDS	-	-	4 866	4 344	4 344	2 724	228	<2
Conductivity (µS/cm)	-	-	9 000	8 900	8 640	7 800	582	11.1

TABLE A.2 CHARACTERIZATION OF QUEEN'S BED MATERIAL (831122E) AND LEACHATES

Parameter	Solids (mg/kg)		Leachates (mg/L)					
	efore Leaching	After Leaching	Cycle 1	Cycle 2	Cycle 5	Cycle 10	Cycle 20	Blank
Aluminum	5 810	30 400	< .01	< .01	< .01	< .01	1.45	< .01
Arsenic	54.9	234	< .005	< .005	< .005	< .005	< .005	< .005
Barium	127	247	.039	< .005	< .005	< .005	.036	< .005
Beryllium	< .05	2.78	< .0005	< .0005	< .0005	< .0005	< .0005	< .0005
Boron	34.6	158	.071	.052	.037	.03	.056	< .004
Cadmium	< 1	< 1	< .01	< .01	< .01	< .01	< .01	< .01
Calcium	404 000	234 000	1 390	1 380	1 410	1 480	65.3	< .01
Chloride	-	-	13.9	6.9	8.3	1.2	2.3	< .1
Chromium	4	69	< .01	< .01	< .01	< .01	< .01	< .01
Cobalt	< 5	< 5	< .05	< .05	< .05	< .05	.06	< .05
Copper	22.5	103	.013	.017	.012	.012	< .009	< .009
Fluoride	-	-	< .1	< .1	< .1	0.4	0.9	< .1
Iron	26 900	144 000	.13	.12	.11	.09	.02	< .01
Lead	< 5	40	< .05	< .05	< .05	< .05	< .05	< .05
Lithium	8	25	-	-	-	-	-	< .01
Magnesium	2 980	15 300	< .01	< .01	< .01	< .01	.10	< .01
Manganese	453	2 280	< .01	< .01	< .01	< .01	< .01	< .01
Molybdenum	< 20	< 20	.3	.2	.3	< .2	.2	< .2
Nickel	29	54	.07	.08	.07	.06	< .05	< .05
Phosphorus	480	2 980	< .6	< .6	< .6	< .6	< .6	< .6
Potassium	900	1 500	1	< 1	< 1	< 1	< 1	<1
Silicon	13 600	71 800	< .05	< .05	< .05	< .05	8.42	< .05
Silver	< 5	< 5	< .005	.014	< .005	< .005	.009	< .005
Sodium	1 400	2 200	< 1	< 1	< 1	< 1	< 1	<1
Strontium	44.7	73.6	.581	.211	.107	< .001	.040	< .001
Sulphate	-	-	1 320	1 317	1 422	1 820	38	<1
Thorium	1.0	-	< .003	< .003	< .003	< .003	< .003	< .003
Titanium	466	2 650	< .005	< .005	< .005	< .005	< .005	< .005
Uranium	3.4	-	.0024	< .001	< .001	.0021	< .001	< .001
Vanadium	41.3	249	< .005	< .005	< .005	< .005	.009	< .005
Zinc	287	1 110	.07	.08	.06	.06	< .05	< .05
Zirconium	17	74	< .05	< .05	< .05	< .05	< .05	< .05
Acidity	-	-	< 1	< 1	< 1	< 1	< 1	<1
Hardness	-	-	3 475	3 450	3 525	3 700	163	<1
pH (units)	-	-	12.4	12.4	12.4	12.3	10.8	7.2
TDS	-	-	4 492	4 490	4 358	4 294	180	<2
Conductivity (µS/cm)	-	-	9 030	9 010	8 900	7 750	520	11.1

TABLE A.3 CHARACTERIZATION OF QUEEN'S BED MATERIAL (831124E) AND LEACHATES

Parameter	Solids (mg/kg)		Leachates (mg/L)					
	Before Leaching	After Leaching	Cycle 1	Cycle 2	Cycle 5	Cycle 10	Cycle 20	Blank
Aluminum	5 720	30 500	< .01	< .01	< .01	< .01	1.61	< .01
Arsenic	50.7	233	< .005	< .005	< .005	< .005	< .005	< .005
Barium	112	232	.045	< .005	< .005	< .005	.049	< .005
Beryllium	< .05	2.20	< .0005	< .0005	< .0005	< .0005	< .0005	< .0005
Boron	49.7	142	.056	.043	.035	.029	.030	< .004
Cadmium	< 1	< 1	< .01	< .01	< .01	< .01	< .01	< .01
Calcium	421 000	236 000	1 320	1 300	1 440	1 490	70.0	< .01
Chloride	-	-	12.9	17.2	16.2	9.5	2.5	< .1
Chromium	5	54	< .01	< .01	< .01	< .01	< .01	< .01
Cobalt	< 5	< 5	< .05	< .05	< .05	< .05	< .05	< .05
Copper	22.7	119	.009	.017	.018	.012	< .009	< .009
Fluoride	-	-	< .1	< .1	< .1	< .1	< .1	< .1
Iron	25 500	141 000	.09	.13	.13	.11	.02	< .01
Lead	< 5	60	< .05	< .05	< .05	< .05	< .05	< .05
Lithium	9	25	-	-	-	-	-	< .01
Magnesium	3 040	15 600	< .01	< .01	< .01	< .01	.07	< .01
Manganese	464	2 620	< .01	< .01	< .01	< .01	< .01	< .01
Molybdenum	< 20	< 20	< .2	.3	.4	< .2	< .2	< .2
Nickel	31	57	.07	.07	.08	.07	< .05	< .05
Phosphorus	410	2 720	< .6	< .6	< .6	< .6	< .6	< .6
Potassium	900	2 200	< 1	1	2	< 1	< 1	<1
Silicon	14 800	82 900	< .05	< .05	.20	< .05	7.71	< .05
Silver	< 5	< 5	< .005	.015	< .005	< .005	.006	< .005
Sodium	900	2 600	< 1	< 1	1	< 1	< 1	<1
Strontium	29.1	28.1	.661	.255	.026	< .001	.033	< .001
Sulphate	-	-	1 376	1 302	1 549	1 477	43	<1
Thorium	.9	-	< .003	< .003	< .003	< .003	< .003	< .003
Titanium	401	2 630	< .005	< .005	< .005	< .005	< .005	< .005
Uranium	3.3	-	.0025	.0010	< .001	< .001	.0018	< .001
Vanadium	35.5	252	< .005	< .005	< .005	< .005	< .005	< .005
Zinc	347	1 360	< .05	.07	.07	.07	< .05	< .05
Zirconium	15	72	< .05	< .05	< .05	< .05	< .05	< .05
Acidity	-	-	< 1	< 1	< 1	< 1	< 1	<1
Hardness	-	-	3 300	3 250	3 600	3 725	175	<1
pH (units)	-	-	12.4	12.5	12.3	12.3	11.0	7.2
TDS	-	-	4 560	4 532	4 330	4 370	174	<2
Conductivity (µS/cm)	-	-	8 980	8 860	8 850	8 550	450	11.1

TABLE A.4 CHARACTERIZATION OF QUEEN'S BED MATERIAL (831213F) AND LEACHATES

Parameter	Solids (mg/kg)		Leachates (mg/L)					
	Before Leaching	After Leaching	Cycle 1	Cycle 2	Cycle 5	Cycle 10	Cycle 20	Blank
Aluminum	4 440	26 300	< .01	< .01	< .01	< .01	< .01	< .01
Arsenic	325	174	< .005	< .005	< .005	< .005	< .005	< .005
Barium	80.0	138	.017	< .005	< .005	< .005	< .005	< .005
Beryllium	< .05	1.17	< .0005	< .0005	< .0005	< .0005	< .0005	< .0005
Boron	21.9	117	.055	.041	.028	.021	.011	< .004
Cadmium	< 1	< 1	< .01	< .01	< .01	< .01	< .01	< .01
Calcium	522 000	283 000	1 320	1 440	1 150	1 070	624	< .01
Chloride	-	-	19.3	3.4	16.2	0.6	2.9	< .1
Chromium	3	26	< .01	< .01	< .01	< .01	< .01	< .01
Cobalt	< 5	< 5	< .05	< .05	< .05	< .05	< .05	< .05
Copper	12.6	56.1	.016	.014	.011	< .009	< .009	< .009
Fluoride	-	-	< .1	< .1	< .1	.2	.3	< .1
Iron	13 500	71 700	.12	.11	.1	.05	.02	< .01
Lead	< 5	15	< .05	< .05	< .05	< .05	< .05	< .05
Lithium	6	9	-	-	-	-	-	< .01
Magnesium	3 740	18 100	< .01	< .01	< .01	< .01	< .01	< .01
Manganese	597	3 000	< .01	< .01	< .01	< .01	< .01	< .01
Molybdenum	< 20	< 20	.4	< .2	.3	< .2	< .2	< .2
Nickel	27	32	.08	.06	.06	.06	< .05	< .05
Phosphorus	300	1 740	.6	< .6	< .6	< .6	< .6	< .6
Potassium	900	2 500	3	< 1	< 1	< 1	< 1	<1
Silicon	13 000	80 000	< .05	< .05	< .05	< .05	.18	< .05
Silver	< 5	< 5	< .005	.008	< .005	< .005	< .005	< .005
Sodium	800	2 200	2	< 1	< 1	< 1	< 1	<1
Strontium	7.7	347	1.31	.368	.371	< .001	< .001	< .001
Sulphate	-	-	1 328	1 333	1 590	595	4	<1
Thorium	.5	-	< .003	< .003	< .003	< .003	< .003	< .003
Titanium	320	1 890	< .005	< .005	< .005	< .005	< .005	< .005
Uranium	2.6	-	< .001	< .001	< .001	< .001	< .001	< .001
Vanadium	14.9	115	< .005	< .005	< .005	< .005	< .005	< .005
Zinc	215	525	.07	.08	< .05	.07	< .05	< .05
Zirconium	16	60	< .05	< .05	< .05	< .05	< .05	< .05
Acidity	-	-	< 1	< 1	< 1	< 1	< 1	<1
Hardness	-	-	3 300	3 600	2 875	2 675	1 560	<1
pH (units)	-	-	12.4	12.4	12.3	12.3	12.2	7.2
TDS	-	-	4 432	4 400	4 322	2 566	1 328	<2
Conductivity (μS/cm)	-	-	8 900	8 880	8 780	8 040	5 600	11.1

TABLE A.5 CHARACTERIZATION OF QUEEN'S BED MATERIAL (831214E) AND LEACHATES

Parameter	Solids (mg/kg)		Leachates (mg/L)					
	Before Leaching	After Leaching	Cycle 1	Cycle 2	Cycle 5	Cycle 10	Cycle 20	Blank
Aluminum	4 920	22 600	< .01	< .01	< .01	< .01	< .01	< .01
Arsenic	23.9	51.8	< .005	< .005	< .005	< .005	< .005	< .005
Barium	91.1	43.1	.019	< .005	< .005	< .005	< .005	< .005
Beryllium	< .05	.92	< .0005	< .0005	< .0005	< .0005	< .0005	< .0005
Boron	22.2	92.7	.044	.037	.029	.022	.016	< .004
Cadmium	< 1	< 1	< .01	< .01	< .01	< .01	< .01	< .01
Calcium	516 000	331 000	1 480	1 190	1 350	825	807	< .01
Chloride	-	-	9.6	8.6	3.5	1.2	0.7	< .1
Chromium	3	32	< .01	< .01	< .01	< .01	< .01	< .01
Cobalt	< 5	< 5	< .05	< .05	< .05	< .05	< .05	< .05
Copper	12.3	38.5	< .009	.012	.011	.009	< .009	< .009
Fluoride	-	-	< .1	< .1	< .1	.2	.2	< .1
Iron	16 500	51 600	.11	.13	.11	.06	.03	< .01
Lead	< 5	< 5	< .05	< .05	< .05	< .05	< .05	< .05
Lithium	4	7	-	-	-	-	-	< .01
Magnesium	3 770	17 200	< .01	< .01	< .01	< .01	< .01	< .01
Manganese	583	2 640	< .01	< .01	< .01	< .01	< .01	< .01
Molybdenum	< 20	< 20	< .2	.3	< .2	.2	< .2	< .2
Nickel	28	28	.07	.06	.07	< .05	< .05	< .05
Phosphorus	280	1 320	< .6	< .6	< .6	< .6	< .6	< .6
Potassium	1 000	1 500	< 1	< 1	< 1	< 1	< 1	<1
Silicon	15 800	64 100	< .05	< .05	< .05	< .05	< .05	< .05
Silver	< 5	< 5	< .005	.013	< .005	< .005	.008	< .005
Sodium	1 100	1 400	< 1	< 1	< 1	< 1	< 1	<1
Strontium	16.7	318	1.58	.568	.225	< .001	< .001	< .001
Sulphate	-	-	1 424	1 296	1 361	357	6	<1
Thorium	.7	-	< .003	< .003	< .003	< .003	< .003	< .003
Titanium	319	1 550	< .005	< .005	< .005	< .005	< .005	< .005
Uranium	2.4	-	.0033	< .001	.0010	< .001	< .001	< .001
Vanadium	12.1	82.4	< .005	< .005	< .005	< .005	< .005	< .005
Zinc	260	584	.09	.06	.08	< .05	.06	< .05
Zirconium	15	51	< .05	< .05	< .05	< .05	< .05	< .05
Acidity	-	-	< 1	< 1	< 1	< 1	< 1	<1
Hardness	-	-	3 700	2 975	3 375	2 065	2 020	<1
pH (units)	-	-	12.5	12.5	12.4	12.4	12.4	7.2
TDS	-	-	4 400	4 470	4 374	2 394	1 730	<2
Conductivity (µS/cm)	-	-	8 840	8 800	8 780	7 970	7 200	11.1

TABLE A.6 CHARACTERIZATION OF QUEEN'S BED MATERIAL (840105E) AND LEACHATES

Parameter	Solids (mg/kg)		Leachates (mg/L)					
	Before Leaching	After Leaching	Cycle 1	Cycle 2	Cycle 5	Cycle 10	Cycle 20	Blank
Aluminum	15 000	59 800	< .01	< .01	< .01	< .01	1.65	< .01
Arsenic	25.2	71.4	< .005	< .005	.021	< .005	< .005	< .005
Barium	139	260	.017	< .005	< .005	< .005	< .005	< .005
Beryllium	< .05	1.52	< .0005	< .0005	< .0005	< .0005	< .0005	< .0005
Boron	41.6	94.6	.057	.041	.029	.018	.008	< .004
Cadmium	< 1	< 1	< .01	< .01	< .01	< .01	< .01	< .01
Calcium	457 000	185 000	1 480	1 260	1 390	850	224	< .01
Chloride	-	-	17.1	4.3	4.1	.2	2.1	< .1
Chromium	29	90	.01	.01	< .01	< .01	< .01	< .01
Cobalt	< 5	< 5	< .05	< .05	< .05	< .05	< .05	< .05
Copper	14.9	47.2	< .009	.015	.012	< .009	< .009	< .009
Fluoride	-	-	< .1	< .1	< .1	.2	.3	< .1
Iron	17 800	65 000	.07	.13	.11	.05	.02	< .01
Lead	160	355	< .05	.20	< .05	< .05	< .05	< .05
Lithium	10	29	-	-	-	-	-	< .01
Magnesium	4 700	17 000	< .01	< .01	< .01	< .01	< .01	< .01
Manganese	585	2 110	< .01	< .01	< .01	< .01	< .01	< .01
Molybdenum	< 20	< 20	< .2	.3	< .2	< .2	< .2	< .2
Nickel	30	98	.06	.07	.07	< .05	< .05	< .05
Phosphorus	250	1 130	< .6	< .6	< .6	< .6	< .6	< .6
Potassium	3 700	13 900	< 1	2	< 1	< 1	< 1	<1
Silicon	31 100	133 000	< .05	< .05	< .05	< .05	1.60	< .05
Silver	< 5	< 5	< .005	.012	< .005	< .005	.007	< .005
Sodium	1 700	5 200	1	< 1	< 1	< 1	< 1	<1
Strontium	23.4	200	1.21	.364	.086	< .001	< .001	< .001
Sulphate	-	-	1 325	1 304	1 107	300	7	<1
Thorium	1.2	-	< .003	< .003	< .003	< .003	< .003	< .003
Titanium	507	2 330	< .005	< .005	< .005	< .005	< .005	< .005
Uranium	2.4	-	< .001	< .001	.0010	< .001	< .001	< .001
Vanadium	15.6	96.8	< .005	< .005	< .005	< .005	.018	< .005
Zinc	588	1 570	.11	.09	.13	.08	< .05	< .05
Zirconium	21	64	< .05	< .05	< .05	< .05	< .05	< .05
Acidity	-	-	< 1	< 1	< 1	< 1	< 1	<1
Hardness	-	-	3 700	3 150	3 475	2 130	560	<1
pH (units)	-	-	12.6	12.7	12.5	12.4	11.9	7.2
TDS	-	-	4 506	4 458	4 308	2 338	516	<2
Conductivity (µS/cm)	-	-	8 990	8 820	8 920	7 750	2 130	11.1

TABLE A.7 CHARACTERIZATION OF SUMMERSIDE BED MATERIAL (831124D) AND LEACHATES

Parameter	Solids (mg/kg)		Leachates (mg/L)					
	Before Leaching	After Leaching	Cycle 1	Cycle 2	Cycle 5	Cycle 10	Cycle 20	Blank
Aluminum	14 200	51 700	< .01	< .01	< .01	< .01	4.16	< .01
Arsenic	310	1 140	< .005	< .005	.038	< .005	< .005	< .005
Barium	154	410	< .005	< .005	< .005	< .005	< .005	< .005
Beryllium	.11	2.94	< .0005	< .0005	< .0005	< .0005	< .0005	< .0005
Boron	24.6	88.3	.041	.036	.031	.024	.009	< .004
Cadmium	< 1	< 1	< .01	< .01	< .01	< .01	< .01	< .01
Calcium	448 000	226 000	1 450	1 380	1 370	1 110	82.1	< .01
Chloride	-	-	12.2	6.4	3.5	.6	1.9	< .1
Chromium	10	56	< .01	< .01	< .01	< .01	< .01	< .01
Cobalt	< 5	< 5	< .05	< .05	< .05	< .05	< .05	< .05
Copper	7.7	25.1	.011	.016	.018	.009	< .009	< .009
Fluoride	-	-	< .1	< .1	< .1	0.4	1.3	< .1
Iron	16 500	67 900	.1	.13	.12	.08	< .01	< .01
Lead	45	150	< .05	< .05	< .05	< 05	< .05	< .05
Lithium	8	24	-	-	-	-	-	< .01
Magnesium	5 350	19 600	< .01	< .01	< .01	< .01	.03	< .01
Manganese	849	3 030	< .01	< .01	< .01	< .01	< .01	< .01
Molybdenum	< 20	< 20	< .2	.3	.4	< .2	< .2	< .2
Nickel	27	35	< .05	.06	.07	< .05	< .05	< .05
Phosphorus	290	1 410	< .6	< .6	< .6	< .6	< .6	< .6
Potassium	2 800	8 700	< 1	< 1	2	< 1	< 1	< 1
Silicon	30 900	135 000	< .05	< .05	< .05	< .05	4.04	< .05
Silver	< 5	< 5	< .005	.007	< .005	< .005	< .005	< .005
Sodium	1 300	2 400	< 1	< 1	< 1	< 1	< 1	< 1
Strontium	123	239	1.15	.409	.206	.039	.059	< .001
Sulphate	-	-	1 413	1 320	824	1 075	68	< 1
Thorium	< .01	-	< .003	< .003	< .003	< .003	< .003	< .003
Titanium	574	2 620	< .005	< .005	< .005	< .005	< .005	< .005
Uranium	< 0.05	-	< .001	< .001	.0016	.0012	< .001	< .001
Vanadium	8.8	69.6	< .005	< .005	< .005	< .005	< .005	< .005
Zinc	209	379	.06	.06	.08	.06	< .05	< .05
Zirconium	20	71	< .05	< .05	< .05	< .05	< .05	< .05
Acidity	-	-	< 1	< 1	< 1	< 1	< 1	< 1
Hardness	-	-	3 625	3 450	3 425	2 775	205	< 1
pH (units)	-	-	12.6	12.6	12.5	12.5	11.1	7.2
TDS	-	-	4 476	4 438	4 304	3 278	212	< 2
Conductivity (µS/cm)	-	-	8 990	8 850	8 910	8 130	570	11.1

TABLE A.8 CHARACTERIZATION OF QUEEN'S CYCLONE MATERIAL (831115E) AND LEACHATES

Parameter	Solids (mg/kg)		Leachates (mg/L)					
	Before Leaching	After Leaching	Cycle 1	Cycle 2	Cycle 5	Cycle 10	Cycle 20	Blank
Aluminum	6 630	15 000	< .01	< .01	< .01	< .01	.27	< .01
Arsenic	6.1	23.9	< .005	< .005	< .005	< .005	< .005	< .005
Barium	128	52	< .005	< .005	.437	.140	.008	< .005
Beryllium	< .05	.92	< .0005	< .0005	< .0005	< .0005	< .0005	< .0005
Boron	40.7	51.6	.080	.048	.019	.016	.015	< .004
Cadmium	3	< 1	< .01	< .01	< .01	< .01	< .01	< .01
Calcium	465 000	237 000	1 400	1 430	743	738	519	< .01
Chloride	-	-	92.1	19.6	0.7	0.5	1.2	< .1
Chromium	< 1	38	< .01	< .01	< .01	< .01	< .01	< .01
Cobalt	< 5	< 5	< .05	< .05	< .05	< .05	< .05	< .05
Copper	25.7	44.0	.014	.015	< .009	< .009	< .009	< .009
Fluoride	-	-	1.9	1.9	15.6	1.2	0.9	< .1
Iron	31 800	69 800	.13	.11	.05	.06	.05	< .01
Lead	35	55	< .05	< .05	< .05	.10	< .05	< .05
Lithium	8	9	-	-	-	-	-	< .01
Magnesium	2 930	6 190	< .01	< .01	< .01	< .01	< .01	< .01
Manganese	544	1 150	< .01	< .01	< .01	< .01	< .01	< .01
Molybdenum	< 20	< 20	.3	< .2	< .2	< .2	.3	< .2
Nickel	28	26	.07	.08	< .05	< .05	< .05	< .05
Phosphorus	340	880	< .6	< .6	< .6	< .6	< .6	< .6
Potassium	1 400	1 200	3	< 1	1	2	< 1	<1
Silicon	20 100	43 900	< .05	< .05	< .05	< .05	.27	< .05
Silver	< 5	< 5	< .005	< .005	< .005	< .005	.013	< .005
Sodium	1 600	1 100	4	2	3	2	< 1	<1
Strontium	13.8	< .1	4.5	2.17	< .001	< .001	< .001	< .001
Sulphate	-	-	1 352	1 467	27	4	2	<1
Thorium	.7	-	< .003	< .003	< .003	< .003	< .003	< .003
Titanium	357	774	< .005	< .005	< .005	< .005	< .005	< .005
Uranium	2.6	-	< .001	.0032	.0010	.0010	.0010	< .001
Vanadium	17.4	51.6	< .005	< .005	< .005	< .005	< .005	< .005
Zinc	483	1 000	< .05	.10	< .05	.06	< .05	< .05
Zirconium	12	17	< .05	< .05	< .05	< .05	< .05	< .05
Acidity	-	-	< 1	< 1	< 1	< 1	< 1	<1
Hardness	-	-	3 500	3 575	1 858	1 845	1 298	<1
pH (units)	-	-	12.4	12.4	12.3	12.4	12.1	7.2
TDS	-	-	4 910	4 468	1 918	1 870	1 198	<2
Conductivity (μS/cm)	-	-	9 160	8 980	7 620	7 310	4 800	11.1

TABLE A.9 CHARACTERIZATION OF QUEEN'S CYCLONE MATERIAL (831122E) AND LEACHATES

Parameter	Solids (mg/kg)		Leachates (mg/L)					
	Before Leaching	After Leaching	Cycle 1	Cycle 2	Cycle 5	Cycle 10	Cycle 20	Blank
Aluminum	11 200	24 800	< .01	< .01	< .01	< .01	4.48	< .01
Arsenic	18.3	39.8	< .005	< .005	< .005	< .005	< .005	< .005
Barium	171	217	.047	< .005	.069	.42	< .005	< .005
Beryllium	.25	1.44	< .0005	< .0005	< .0005	< .0005	< .0005	< .0005
Boron	58.0	58.1	.184	.063	.03	.018	.080	< .004
Cadmium	12	< 1	< .01	< .01	< .01	< .01	< .01	< .01
Calcium	312 000	97 900	1 570	1 350	1 020	802	51.1	< .01
Chloride	-	-	98.6	11.5	1.4	1.6	1.3	< .1
Chromium	5	48	< .01	< .01	< .01	< .01	< .01	< .01
Cobalt	< 5	< 5	< .05	< .05	< .05	< .05	< .05	< .05
Copper	35.2	65.0	< .009	.016	.012	< .009	< .009	< .009
Fluoride	-	-	2.6	2.5	1.9	1.4	0.6	<1
Iron	66 400	148 000	.11	.15	.07	.06	.01	< .01
Lead	95	140	< .05	.10	< .05	< .05	< .05	< .05
Lithium	14	15	-	-	-	-	-	< .01
Magnesium	2 480	5 120	< .01	< .01	< .01	< .01	.04	< .01
Manganese	394	809	< .01	< .01	< .01	< .01	< .01	< .01
Molybdenum	< 20	< 20	< .2	.2	.3	< .2	< .2	< .2
Nickel	37	40	.06	.07	.06	< .05	< .05	< .05
Phosphorus	510	1 280	< .6	< .6	< .6	< .6	< .6	< .6
Potassium	2 200	2 700	< 1	< 1	2	2	< 1	<1
Silicon	36 200	75 200	< .05	< .05	.07	< .05	3.62	< .05
Silver	< 5	< 5	< .005	.012	< .005	< .005	< .005	< .005
Sodium	2 400	3 100	7	2	3	3	< 1	<1
Strontium	31.9	21.6	1.89	1.08	.044	< .001	< .001	< .001
Sulphate	-	-	1 544	1 317	743	4	42	<1
Thorium	1.4	-	< .003	< .003	< .003	< .003	< .003	< .003
Titanium	512	1 060	< .005	< .005	< .005	< .005	< .005	< .005
Uranium	3.2	-	.0036	< .001	.0010	.0018	< .001	< .001
Vanadium	51.2	99.9	< .005	< .005	< .005	< .005	.019	< .005
Zinc	999	1 780	.17	.18	.11	.11	< .05	< .05
Zirconium	16	22	< .05	< .05	< .05	< .05	< .05	< .05
Acidity	-	-	< 1	< 1	< 1	< 1	< 1	<1
Hardness	-	-	3 925	3 375	2 550	2 000	130	<1
pH (units)	-	-	12.5	12.5	12.4	12.4	10.9	7.2
TDS	-	-	4 878	4 494	2 860	1 672	132	<2
Conductivity (μS/cm)	-	-	9 270	9 090	8 170	7 250	370	11.1

TABLE A.10 CHARACTERIZATION OF QUEEN'S CYCLONE MATERIAL (831124E) AND LEACHATES

Parameter	Solids (mg/kg)		Leachates (mg/L)					
	Before Leaching	After Leaching	Cycle 1	Cycle 2	Cycle 5	Cycle 10	Cycle 20	Blank
Aluminum	9 200	25 900	< .01	< .01	< .01	< .01	3.33	< .01
Arsenic	17.9	41.9	< .005	< .005	< .005	< .005	< .005	< .005
Barium	149	167	< .005	< .005	< .005	.404	< .005	< .005
Beryllium	.09	1.52	< .0005	< .0005	< .0005	< .0005	< .0005	< .0005
Boron	53.7	72.8	.144	.057	.036	.018	.052	< .004
Cadmium	8	< 1	< .01	< .01	< .01	< .01	< .01	< .01
Calcium	373 000	119 000	1 490	1 280	1 330	733	84.4	< .01
Chloride	-	-	69.6	10.3	2.6	1.3	2.4	< .1
Chromium	12	30	< .01	< .01	< .01	< .01	< .01	< .01
Cobalt	< 5	< 5	< .05	< .05	< .05	< .05	< .05	< .05
Copper	32.7	84.7	.010	.016	.018	.012	< .009	< .009
Fluoride	-	-	3.2	2.5	1.4	1.0	1.2	< .1
Iron	47 300	125 000	.10	.11	.13	.06	.02	< .01
Lead	75	190	< .05	.05	.05	.10	< .05	< .05
Lithium	12	15	-	-	-	-	-	< .01
Magnesium	2 910	7 240	< .01	< .01	< .01	< .01	.03	< .01
Manganese	495	1 330	< .01	< .01	< .01	< .01	< .01	< .01
Molybdenum	< 20	< 20	< .2	.3	.4	.2	.2	< .2
Nickel	36	38	.08	.07	.08	< .05	< .05	< .05
Phosphorus	420	1 280	< .6	< .6	< .6	< .6	< .6	< .6
Potassium	1 900	2 800	< 1	2	4	3	< 1	<1
Silicon	30 000	82 000	< .05	< .05	.08	< .05	5.91	< .05
Silver	< 5	< 5	< .005	.014	< .005	< .005	.008	< .005
Sodium	1 800	2 700	4	2	2	3	1	<1
Strontium	5.9	< .1	1.29	.869	.458	< .001	.022	< .001
Sulphate	-	-	1 408	1 310	1 497	10	64	<1
Thorium	.9	-	< .003	< .003	< .003	< .003	< .003	< .003
Titanium	430	1 150	< .005	< .005	< .005	< .005	< .005	< .005
Uranium	1.6	-	.0010	.0010	< .001	.0020	.0010	< .001
Vanadium	37.6	99.6	< .005	< .005	< .005	< .005	.060	< .005
Zinc	872	1 900	.12	.12	.11	.07	< .05	< .05
Zirconium	14	26	< .05	< .05	< .05	< .05	< .05	< .05
Acidity	-	-	< 1	< 1	< 1	< 1	< 1	<1
Hardness	-	-	3 725	3 200	3 325	1 833	220	<1
pH (units)	-	-	12.4	12.5	12.4	12.3	11.1	7.2
TDS	-	-	4 808	4 658	4 286	1 870	212	<2
Conductivity (μS/cm)	-	-	9 200	9 020	8 500	7 450	577	11.1

TABLE A.11 CHARACTERIZATION OF QUEEN'S CYCLONE MATERIAL (831213E) AND LEACHATES

Parameter	Solids (mg/kg)		Leachates (mg/L)					
	Before Leaching	After Leaching	Cycle 1	Cycle 2	Cycle 5	Cycle 10	Cycle 20	Blank
Aluminum	13 100	27 100	< .01	< .01	< .01	< .01	2.99	< .01
Arsenic	25.1	50.9	< .005	< .005	< .005	< .005	< .005	< .005
Barium	220	200	.018	< .005	< .005	.385	< .005	< .005
Beryllium	.25	1.59	< .0005	< .0005	< .0005	< .0005	< .0005	< .0005
Boron	71.1	91.8	.188	.067	.032	.017	.083	< .004
Cadmium	14	< 1	< .01	< .01	< .01	< .01	< .01	< .01
Calcium	368 000	117 000	1 540	1 330	1 180	774	71.3	< .01
Chloride	-	-	94.3	7.5	17.3	.6	1.8	< .1
Chromium	< 1	3	< .01	< .01	< .01	< .01	< .01	< .01
Cobalt	< 5	< 5	< .05	< .05	< .05	< .05	< .05	< .05
Copper	39.7	79.7	.012	.015	.009	< .009	< .009	< .009
Fluoride	-	-	3.2	2.6	2.5	1.4	1.1	< .1
Iron	78 800	180 000	.13	.11	.11	.06	< .01	< .01
Lead	90	125	< .05	< .05	< .05	< .05	< .05	< .05
Lithium	15	19	-	-	-	-	-	< .01
Magnesium	2 470	5 640	< .01	< .01	< .01	< .01	.02	< .01
Manganese	459	1 000	< .01	< .01	< .01	< .01	< .01	< .01
Molybdenum	< 20	< 20	.2	.3	.2	< .2	< .2	< .2
Nickel	37	47	.07	.06	.06	< .05	< .05	< .05
Phosphorus	590	1 530	< .6	< .6	< .6	< .6	< .6	< .6
Potassium	2 100	2 900	4	3	< 1	2	< 1	<1
Silicon	35 300	81 000	< .05	< .05	< .05	< .05	5.51	< .05
Silver	< 5	< 5	< .005	.013	< .005	< .005	< .005	< .005
Sodium	2 600	3 500	8	2	2	2	< 1	<1
Strontium	8.7	36.4	1.33	.769	.233	< .001	.094	< .001
Sulphate	-	-	1 480	1 336	1 312	8	54	<1
Thorium	1.3	-	< .003	< .003	< .003	< .003	< .003	< .003
Titanium	517	1 180	< .005	< .005	< .005	< .005	< .005	< .005
Uranium	3.0	-	< .001	< .001	< .001	.0010	< .001	< .001
Vanadium	55.5	115	< .005	< .005	< .005	< .005	< .005	< .005
Zinc	858	1 820	.18	.18	.19	.11	< .05	< .05
Zirconium	16	28	< .05	< .05	< .05	< .05	< .05	< .05
Acidity	-	-	< 1	< 1	< 1	< 1	< 1	<1
Hardness	-	-	3 850	3 325	2 950	1 935	178	<1
pH (units)	-	-	12.5	12.6	12.3	12.4	11.1	7.2
TDS	-	-	4 782	4 576	3 636	1 862	196	<2
Conductivity (μS/cm)	-	-	9 150	8 920	8 580	7 420	544	11.1

TABLE A.12 CHARACTERIZATION OF QUEEN'S CYCLONE MATERIAL (831214E) AND LEACHATES

Parameter	Solids (mg/kg)		Leachates (mg/L)					
	Before Leaching	After Leaching	Cycle 1	Cycle 2	Cycle 5	Cycle 10	Cycle 20	Blank
Aluminum	12 200	29 400	< .01	< .01	< .01	< .01	< .01	< .01
Arsenic	26.1	41.8	< .005	< .005	< .005	< .005	< .005	< .005
Barium	160	229	.025	< .005	< .005	.399	< .005	< .005
Beryllium	.16	1.88	< .0005	< .0005	< .0005	< .0005	< .0005	< .0005
Boron	65.1	84.2	.179	.071	.031	.019	.084	< .004
Cadmium	13	< 1	< .01	< .01	< .01	< .01	< .01	< .01
Calcium	407 000	124 000	1 510	1 480	1 300	728	90.9	< .01
Chloride	-	-	118	16.1	23.7	2.3	2.4	< .1
Chromium	7	10	< .01	< .01	< .01	< .01	< .01	< .01
Cobalt	< 5	< 5	< .05	< .05	< .05	< .05	< .05	< .05
Copper	32.8	89.2	.013	.013	< .009	< .009	< .009	< .009
Fluoride	-	-	2.5	1.9	2.2	1.2	1.2	< .1
Iron	69 400	195 000	.11	.13	.06	.06	< .01	< .01
Lead	60	110	< .05	< .05	< .05	< .05	< .05	< .05
Lithium	11	22	-	-	-	-	-	< .01
Magnesium	2 730	7 700	< .01	< .01	< .01	< .01	.02	< .01
Manganese	501	1 370	< .01	< .01	< .01	< .01	< .01	< .01
Molybdenum	< 20	< 20	< .2	.3	< .2	.3	< .2	< .2
Nickel	38	49	.06	.08	.06	< .05	< .05	< .05
Phosphorus	530	1 600	< .6	< .6	< .6	< .6	< .6	< .6
Potassium	2 400	3 200	4	< 1	< 1	< 1	< 1	<1
Silicon	31 500	90 300	< .05	< .05	< .05	< .05	5.13	< .05
Silver	< 5	< 5	< .005	.011	< .005	< .005	< .005	< .005
Sodium	2 700	3 900	6	1	< 1	2	< 1	<1
Strontium	7.1	49.3	.984	.528	.266	< .001	.185	< .001
Sulphate	-	-	1 325	1 456	1 531	9	63	<1
Thorium	.9	-	< .003	< .003	< .003	< .003	< .003	< .003
Titanium	467	1 250	< .005	< .005	< .005	< .005	< .005	< .005
Uranium	2.6	-	< .001	.0012	< .001	.0014	< .001	< .001
Vanadium	44.2	128	< .005	< .005	< .005	< .005	.032	< .005
Zinc	898	2 460	.15	.24	.13	.11	< .05	< .05
Zirconium	20	36	< .05	< .05	< .05	< .05	< .05	< .05
Acidity	-	-	< 1	< 1	< 1	< 1	< 1	<1
Hardness	-	-	3 775	3 700	3 250	1 820	225	<1
pH (units)	-	-	12.6	12.6	12.6	12.4	11.2	7.2
TDS	-	-	4 786	4 562	4 374	1 798	228	<2
Conductivity (μS/cm)	-	-	9 110	9 000	8 800	7 480	700	11.1

TABLE A.13 CHARACTERIZATION OF QUEEN'S CYCLONE MATERIAL (840105E) AND LEACHATES

Parameter	Solids (mg/kg)		Leachates (mg/L)					
	Before Leaching	After Leaching	Cycle 1	Cycle 2	Cycle 5	Cycle 10	Cycle 20	Blank
Aluminum	31 000	67 300	< .01	< .01	< .01	1.24	1.91	< .01
Arsenic	55.1	76.8	< .005	< .005	.024	< .005	< .005	< .005
Barium	245	377	.024	< .005	< .005	.11	.009	< .005
Beryllium	.55	2.09	< .0005	< .0005	< .0005	< .0005	< .0005	< .0005
Boron	82.1	111	.169	.055	.033	.009	.078	< .004
Cadmium	26	< 1	< .01	< .01	< .01	< .01	< .01	< .01
Calcium	279 000	52 800	1 470	1 340	1 290	84.9	46.8	< .01
Chloride	-	-	35.4	10.7	8.1	1.4	1.3	< .1
Chromium	51	45	< .01	< .01	< .01	< .01	< .01	< .01
Cobalt	< 5	< 5	< .05	< .05	< .05	< .05	< .05	< .05
Copper	43.1	85.1	< .009	.012	< .009	< .009	< .009	< .009
Fluoride	-	-	< .1	< .1	.9	.3	.7	< .1
Iron	95 700	203 000	.07	.12	.08	< .01	.02	< .01
Lead	250	345	< .05	.25	< .05	< .05	< .05	< .05
Lithium	29	50	-	-	-	-	-	< .01
Magnesium	8 350	16 100	< .01	< .01	.01	.01	.13	< .01
Manganese	761	1 380	< .01	< .01	< .01	< .01	< .01	< .01
Molybdenum	< 20	< 20	< .2	< .2	< .2	< .2	< .2	< .2
Nickel	48	53	< .05	.07	< .05	< .05	< .05	< .05
Phosphorus	520	1 170	< .6	< .6	< .6	< .6	< .6	< .6
Potassium	8 200	14 400	1	< 1	< 1	< 1	< 1	<1
Silicon	59 700	141 000	< .05	< .05	< .05	1.31	7.57	< .05
Silver	< 5	< 5	< .005	< .005	< .005	< .005	< .005	< .005
Sodium	4 200	7 300	3	< 1	1	3	< 1	<1
Strontium	3.1	79.7	.274	.067	< .001	< .001	.011	< .001
Sulphate	-	-	1 357	1 416	1 531	25	27	<1
Thorium	2.5	-	< .003	< .003	< .003	< .003	< .003	< .003
Titanium	1 050	2 260	< .005	< .005	< .005	< .005	< .005	< .005
Uranium	1.8	-	.0028	< .001	.0027	< .001	< .001	< .001
Vanadium	75.5	132	< .005	< .005	< .005	< .005	.035	< .005
Zinc	2 410	4 580	.47	.46	.25	< .05	< .05	< .05
Zirconium	33	56	< .05	< .05	< .05	< .05	< .05	< .05
Acidity	-	-	< 1	< 1	< 1	< 1	< 1	<1
Hardness	-	-	3 675	3 350	3 230	221	115	<1
pH (units)	-	-	12.7	12.7	12.5	11.8	10.8	7.2
TDS	-	-	4 686	4 596	4 266	514	124	<2
Conductivity (μS/cm)	-	-	9 240	9 110	8 950	2 050	340	11.1

TABLE A.14 CHARACTERIZATION OF QUEEN'S BAGHOUSE MATERIAL (831115E) AND LEACHATES

Parameter	Solids (mg/kg)		Leachates (mg/L)					
	Before Leaching	After Leaching	Cycle 1	Cycle 2	Cycle 5	Cycle 10	Cycle 20	Blank
Aluminum	43 200	46 300	< .01	< .01	4.27	1.28	6.94	< .01
Arsenic	75.0	89.1	< .005	< .005	< .005	< .005	< .005	< .005
Barium	677	644	.377	.248	.504	.054	.050	< .005
Beryllium	3.39	5.28	< .0005	< .0005	< .0005	< .0005	< .0005	< .0005
Boron	70.8	92.4	.043	.028	.075	.143	.120	< .004
Cadmium	40	< 1	< .01	< .01	< .01	< .01	< .01	< .01
Calcium	202 000	125 000	1 790	1 050	61.7	43.6	75.7	< .01
Chloride	-	-	435	66.4	6.2	1.0	1.9	< .1
Chromium	24	60	< .01	< .01	< .01	< .01	< .01	< .01
Cobalt	< 5	< 5	< .05	< .05	< .05	< .05	< .05	< .05
Copper	128	139	.015	.015	< .009	< .009	< .009	< .009
Fluoride	-	-	3.2	3.1	1.4	0.5	0.7	< .1
Iron	173 000	212 000	.13	.11	.05	< .01	.02	< .01
Lead	400	500	< .05	.65	< .05	< .05	< .05	< .05
Lithium	53	61	-	-	-	-	-	< .01
Magnesium	2 910	3 410	< .01	< .01	.03	.04	.02	< .01
Manganese	413	499	< .01	< .01	< .01	< .01	< .01	< .01
Molybdenum	< 20	< 20	.6	.4	< .2	< .2	< .2	< .2
Nickel	91	102	.08	.07	< .05	< .05	< .05	< .05
Phosphorus	2 320	2 760	< .6	< .6	< .6	< .6	< .6	< .6
Potassium	8 100	7 100	14	6	2	3	< 1	<1
Silicon	66 100	82 400	< .05	.07	1.05	.47	2.94	< .05
Silver	< 5	< 5	< .005	.008	< .005	< .005	.006	< .005
Sodium	10 300	7 900	35	8	3	2	1	<1
Strontium	246	172	2.39	1.24	.206	.039	.018	< .001
Sulphate	-	-	748	841	37	79	71	<1
Thorium	3.7	-	< .003	< .003	< .003	< .003	< .003	< .003
Titanium	2 060	2 710	< .005	< .005	< .005	< .005	< .005	< .005
Uranium	7.3	-	.0043	< .001	.0010	.0010	< .001	< .001
Vanadium	244	271	< .005	< .005	.007	.053	.007	< .005
Zinc	1 390	1 490	.08	.08	< .05	< .05	< .05	< .05
Zirconium	42	56	< .05	< .05	< .05	< .05	< .05	< .05
Acidity	-	-	< 1	< 1	< 1	< 1	< 1	<1
Hardness	-	-	4 475	2 625	154	109	192	<1
pH (units)	-	-	12.4	12.3	11.6	11.0	10.9	7.2
TDS	-	-	5 548	3 128	376	254	206	<2
Conductivity (µS/cm)	-	-	10 820	7 950	1 400	640	510	11.1

TABLE A.15 CHARACTERIZATION OF QUEEN'S BAGHOUSE MATERIAL (831122E) AND LEACHATES

Parameter	Solids (mg/kg)		Leachates (mg/L)					
	Before Leaching	After Leaching	Cycle 1	Cycle 2	Cycle 5	Cycle 10	Cycle 20	Blank
Aluminum	49 100	60 000	< .01	< .01	1.66	1.51	6.39	< .01
Arsenic	100	149	< .005	< .005	< .005	< .005	0.017	< .005
Barium	893	1 010	.903	.562	.134	.070	.075	< .005
Beryllium	4.69	6.76	< .0005	< .0005	< .0005	< .0005	< .0005	< .0005
Boron	158	42.1	.089	.215	.204	.204	.216	< .004
Cadmium	50	< 1	< .01	< .01	< .01	< .01	< .01	< .01
Calcium	101 000	58 000	1 220	622	79.8	60.5	55.8	< .01
Chloride	-	-	679	73.8	3.3	2.4	1.1	< .1
Chromium	39	74	< .01	< .01	< .01	< .01	< .01	< .01
Cobalt	< 5	< 5	< .05	< .05	< .05	< .05	< .05	< .05
Copper	177	204	< .009	< .009	< .009	< .009	< .009	< .009
Fluoride	-	-	5.0	1.3	1.2	1.6	1.5	< .1
Iron	229 000	285 000	.08	.06	.03	< .01	.01	< .01
Lead	890	1 100	.65	< .05	< .05	< .05	< .05	< .05
Lithium	66	79	-	-	-	-	-	< .01
Magnesium	2 930	3 410	< .01	.26	.14	.07	.03	< .01
Manganese	348	433	< .01	< .01	< .01	< .01	< .01	< .01
Molybdenum	< 20	< 20	.6	.3	< .2	< .2	< .2	< .2
Nickel	107	118	< .05	< .05	< .05	< .05	< .05	< .05
Phosphorus	2 900	3 790	< .6	< .6	< .6	< .6	< .6	< .6
Potassium	9 000	8 800	28	6	2	< 1	< 1	<1
Silicon	84 300	103 000	.54	10.6	5.89	.81	2.46	< .05
Silver	< 5	< 5	< .005	< .005	< .005	< .005	< .005	< .005
Sodium	12 100	9 700	104	21	2	< 1	< 1	<1
Strontium	303	282	2.30	1.37	.121	.014	.009	< .001
Sulphate	-	-	1 536	1 321	184	115	53	<1
Thorium	5.9	-	< .003	< .003	< .003	< .003	< .003	< .003
Titanium	3 090	3 780	< .005	< .005	< .005	< .005	< .005	< .005
Uranium	10.0	-	< .001	< .001	< .001	.0019	< .001	< .001
Vanadium	325	352	< .005	.239	.215	.071	.021	< .005
Zinc	1 990	2 130	< .05	< .05	< .05	< .05	< .05	< .05
Zirconium	47	75	< .05	< .05	< .05	< .05	< .05	< .05
Acidity	-	-	< 1	< 1	< 1	< 1	< 1	<1
Hardness	-	-	3 050	1 555	200	151	140	<1
pH (units)	-	-	12.0	11.5	11.1	11	10.4	7.2
TDS	-	-	4 476	2 384	394	256	148	<2
Conductivity (μS/cm)	-	-	6 580	2 590	605	480	310	11.1

TABLE A.16 CHARACTERIZATION OF QUEEN'S BAGHOUSE MATERIAL (831124E) AND LEACHATES

Parameter	Solids (mg/kg)		Leachates (mg/L)					
	Before Leaching	After Leaching	Cycle 1	Cycle 2	Cycle 5	Cycle 10	Cycle 20	Blank
Aluminum	40 900	55 300	< .01	< .01	.56	5.72	4.15	< .01
Arsenic	101	99.6	< .005	< .005	< .005	< .005	< .005	< .005
Barium	697	882	.470	.269	.103	.077	.098	< .005
Beryllium	2.94	5.89	< .0005	< .0005	< .0005	< .0005	< .0005	< .0005
Boron	137	59.5	.119	.034	.158	.253	.146	< .004
Cadmium	39	< 1	< .01	< .01	< .01	< .01	< .01	< .01
Calcium	123 000	44 700	1 630	1 070	141	51.7	46.5	< .01
Chloride	-	-	219	36.3	5.2	4.6	1.1	< .1
Chromium	46	61	< .01	< .01	< .01	< .01	< .01	< .01
Cobalt	< 5	< 5	< .05	< .05	< .05	< .05	< .05	< .05
Copper	138	222	< .009	.013	< .009	< .009	< .009	< .009
Fluoride	-	-	3.2	3.8	0.6	0.9	0.7	< .1
Iron	203 000	303 000	.30	.10	.05	.02	.02	< .01
Lead	810	1 050	3.2	.80	< .05	< .05	< .05	< .05
Lithium	60	69	-	-	-	-	-	< .01
Magnesium	2 600	3 120	< .01	< .01	.25	.07	.06	< .01
Manganese	305	433	< .01	< .01	< .01	< .01	< .01	< .01
Molybdenum	< 20	< 20	.6	.4	.3	< .2	< .2	< .2
Nickel	91	107	.08	.06	< .05	< .05	< .05	< .05
Phosphorus	2 040	3 290	.6	< .6	< .6	< .6	< .6	< .6
Potassium	6 600	8 500	17	3	3	< 1	< 1	<1
Silicon	72 300	95 200	< .05	.22	5.35	2.13	3.41	< .05
Silver	< 5	< 5	< .005	.009	.008	< .005	< .005	< .005
Sodium	8 000	10 400	78	11	3	1	< 1	<1
Strontium	221	226	1.54	.902	.173	.006	.024	< .001
Sulphate	-	-	1 752	1 625	330	67	41	<1
Thorium	4.9	-	< .003	< .003	< .003	< .003	< .003	< .003
Titanium	1 880	3 220	< .005	< .005	< .005	< .005	< .005	< .005
Uranium	10.0	-	< .001	.0018	< .001	< .001	.0010	< .001
Vanadium	264	313	< .005	< .005	.251	.081	.090	< .005
Zinc	1 890	2 500	.24	.14	< .05	< .05	< .05	< .05
Zirconium	35	62	< .05	< .05	< .05	< .05	< .05	< .05
Acidity	-	-	< 1	< 1	< 1	< 1	< 1	<1
Hardness	-	-	4 075	2 675	360	144	117	<1
pH (units)	-	-	12.5	12.2	11.3	11.2	10.3	7.2
TDS	-	-	5 358	3 766	568	212	120	<2
Conductivity (µS/cm)	-	-	11 390	6 700	920	440	294	11.1

TABLE A.17 CHARACTERIZATION OF QUEEN'S BAGHOUSE MATERIAL (831213F) AND LEACHATES

Parameter	Solids (mg/kg)		Leachates (mg/L)					
	Before Leaching	After Leaching	Cycle 1	Cycle 2	Cycle 5	Cycle 10	Cycle 20	Blank
Aluminum	54 800	63 100	< .01	< .01	.48	1.41	3.81	< .01
Arsenic	115	129	< .005	< .005	< .005	< .005	.014	< .005
Barium	796	990	.942	.512	.188	.071	.065	< .005
Beryllium	5.01	8.19	< .0005	< .0005	< .0005	< .0005	< .0005	< .0005
Boron	196	124	.106	.066	.177	.196	.184	< .004
Cadmium	54	< 1	< .01	< .01	< .01	< .01	< .01	< .01
Calcium	140 000	73 900	1 600	922	130	43.7	49.6	< .01
Chloride	-	-	217	45.6	1.8	1.1	0.8	< .1
Chromium	33	64	< .01	< .01	< .01	< .01	< .01	< .01
Cobalt	< 5	< 5	< .05	< .05	< .05	< .05	< .05	< .05
Copper	229	251	.013	.011	< .009	< .009	< .009	< .009
Fluoride	-	-	4.5	2.5	.6	.8	.8	< .1
Iron	203 000	273 000	.12	.11	< .01	< .01	< .01	< .01
Lead	865	900	5.21	.61	< .05	< .05	< .05	< .05
Lithium	69	91	-	-	-	-	-	< .01
Magnesium	3 370	4 220	< .01	< .01	.21	.07	.05	< .01
Manganese	407	502	< .01	< .01	< .01	< .01	< .01	< .01
Molybdenum	< 20	< 20	.8	.5	< .2	< .2	< .2	< .2
Nickel	122	129	.07	.06	< .05	< .05	< .05	< .05
Phosphorus	3 220	4 230	.6	< .6	< .6	< .6	< .6	< .6
Potassium	9 900	9 000	47	9	< 1	3	< 1	<1
Silicon	78 500	102 000	< .05	.67	9.61	.85	4.54	< .05
Silver	< 5	< 5	< .005	.011	< .005	< .005	< .005	< .005
Sodium	13 400	10 300	113	16	3	2	< 1	<1
Strontium	339	330	1.81	.979	.267	.035	.038	< .001
Sulphate	-	-	1 792	1 429	309	75	43	<1
Thorium	1.9	-	< .003	< .003	< .003	< .003	< .003	< .003
Titanium	3 670	4 490	< .005	< .005	< .005	< .005	< .005	< .005
Uranium	7.4	-	< .001	< .001	< .001	< .001	.0010	< .001
Vanadium	405	430	< .005	< .005	.326	.082	.028	< .005
Zinc	2 500	2 800	.40	< .05	< .05	< .05	< .05	< .05
Zirconium	60	80	< .05	< .05	< .05	< .05	< .05	< .05
Acidity	-	-	< 1	< 1	< 1	< 1	< 1	<1
Hardness	-	-	4 000	2 305	340	122	122	<1
pH (units)	-	-	12.4	12.0	11.4	11.1	10.5	7.2
TDS	-	-	5 514	3 354	604	216	132	<2
Conductivity (µS/cm)	-	-	11 170	4 900	950	475	325	11.1

TABLE A.18 CHARACTERIZATION OF QUEEN'S BAGHOUSE MATERIAL (831214F) AND LEACHATES

Parameter	Solids (mg/kg)		Leachates (mg/L)					
	Before Leaching	After Leaching	Cycle 1	Cycle 2	Cycle 5	Cycle 10	Cycle 20	Blank
Aluminum	46 100	59 100	< .01	< .01	< .01	.93	4.43	< .01
Arsenic	100	119	< .005	< .005	< .005	< .005	< .005	< .005
Barium	576	820	.562	.358	.122	.053	.092	< .005
Beryllium	3.39	6.62	< .0005	< .0005	< .0005	< .0005	< .0005	< .0005
Boron	142	126	.079	.048	.024	.211	.138	< .004
Cadmium	40	< 1	< .01	< .01	< .01	< .01	< .01	< .01
Calcium	209 000	92 900	1 790	1 410	315	45.2	61.8	< .01
Chloride	-	-	272	42.9	3.6	1.3	2.3	< .1
Chromium	33	50	< .01	< .01	< .01	< .01	< .01	< .01
Cobalt	< 5	< 5	< .05	< .05	< .05	< .05	< .05	< .05
Copper	169	230	.012	.029	< .009	< .009	< .009	< .009
Fluoride	-	-	3.1	3.2	.9	.4	.9	< .1
Iron	185 000	263 000	.11	.12	.04	.02	< .01	< .01
Lead	550	750	1.95	1.31	< .05	< .05	< .05	< .05
Lithium	62	79	-	-	-	-	-	< .01
Magnesium	3 340	4 580	< .01	< .01	.09	.07	.02	< .01
Manganese	442	592	< .01	< .01	< .01	< .01	< .01	< .01
Molybdenum	< 20	< 20	.6	.3	.4	< .2	< .2	< .2
Nickel	101	120	.07	.06	< .05	< .05	< .05	< .05
Phosphorus	2 510	3 810	< .6	< .6	< .6	< .6	< .6	< .6
Potassium	8 700	8 400	45	5	9	2	< 1	<1
Silicon	62 800	92 500	.11	< .05	5.69	1.85	3.7	< .05
Silver	< 5	< 5	< .005	< .005	< .005	< .005	< .005	< .005
Sodium	10 500	9 400	86	13	11	2	< 1	<1
Strontium	259	285	1.42	.559	.906	.036	.086	< .001
Sulphate	-	-	1 603	1 728	740	70	58	<1
Thorium	.4	-	< .003	< .003	< .003	< .003	< .003	< .003
Titanium	2 970	4 020	< .005	< .005	< .005	< .005	< .005	< .005
Uranium	22.6	-	< .001	.0012	< .001	.0010	< .001	< .001
Vanadium	321	409	< .005	< .005	.081	.101	.049	< .005
Zinc	2 200	2 850	.23	.13	< .05	< .05	< .05	< .05
Zirconium	48	81	< .05	< .05	< .05	< .05	< .05	< .05
Acidity	-	-	< 1	< 1	< 1	< 1	< 1	<1
Hardness	-	-	4 475	3 525	800	119	155	<1
pH (units)	-	-	12.5	12.5	11.5	11.2	10.8	7.2
TDS	-	-	5 460	4 384	1 302	226	170	<2
Conductivity (μS/cm)	-	-	10 490	8 840	2 070	550	420	11.1

TABLE A.19 CHARACTERIZATION OF QUEEN'S BAGHOUSE MATERIAL (840105E) AND LEACHATES

Parameter	Solids (mg/kg)		Leachates (mg/L)					
	Before Leaching	After Leaching	Cycle 1	Cycle 2	Cycle 5	Cycle 10	Cycle 20	Blank
Aluminum	41 300	56 800	< .01	< .01	.61	4.74	2.33	< .01
Arsenic	90.3	169	< .005	< .005	< .005	< .005	.035	< .005
Barium	500	598	1.03	.446	.122	.034	.048	< .005
Beryllium	2.72	4.81	< .0005	< .0005	< .0005	< .0005	< .0005	< .0005
Boron	129	111	.222	.103	.156	.314	.102	< .004
Cadmium	47	< 1	< .01	< .01	< .01	< .01	< .01	< .01
Calcium	121 000	36 700	1 690	1 070	166	42.6	34.9	< .01
Chloride	-	-	271	31.1	2.1	.9	1.1	< .1
Chromium	79	68	< .01	< .01	< .01	< .01	< .01	< .01
Cobalt	< 5	< 5	< .05	< .05	< .05	< .05	< .05	< .05
Copper	122	163	.011	< .009	< .009	< .009	< .009	< .009
Fluoride	-	-	5.6	2.6	.6	.7	.8	< .1
Iron	173 000	228 000	.07	.09	< .01	< .01	< .01	< .01
Lead	850	1 000	3.41	.91	< .05	< .05	< .05	< .05
Lithium	56	75	-	-	-	-	-	< .01
Magnesium	3 730	4 850	< .01	< .01	.25	.06	.07	< .01
Manganese	383	491	< .01	< .01	< .01	< .01	< .01	< .01
Molybdenum	< 20	< 20	.6	.3	< .2	< .2	< .2	< .2
Nickel	89	91	.08	< .05	< .05	< .05	< .05	< .05
Phosphorus	1 460	2 030	< .6	< .6	< .6	< .6	< .6	< .6
Potassium	8 500	9 700	13	< 1	< 1	< 1	< 1	<1
Silicon	73 700	93 200	< .05	< .05	6.38	1.26	6.86	< .05
Silver	< 5	< 5	< .005	< .005	< .005	< .005	< .005	< .005
Sodium	8 700	8 500	52	5	2	1	< 1	<1
Strontium	185	184	1.17	.455	.211	.004	.042	< .001
Sulphate	-	-	1 627	1 648	375	71	18	<1
Thorium	4.6	-	< .003	< .003	< .003	< .003	< .003	< .003
Titanium	2 080	2 980	< .005	< .005	< .005	< .005	< .005	< .005
Uranium	8.1	-	< .001	< .001	.0015	< .001	< .001	< .001
Vanadium	282	292	< .005	< .005	.253	.064	.069	< .005
Zinc	3 960	4 350	1.89	.62	< .05	< .05	< .05	< .05
Zirconium	47	63	< .05	< .05	< .05	< .05	< .05	< .05
Acidity	-	-	< 1	< 1	< 1	< 1	< 1	<1
Hardness	-	-	4 225	2 675	430	117	88	<1
pH (units)	-	-	12.4	12.1	11.4	11.3	10.6	7.2
TDS	-	-	5 258	3 416	666	216	124	<2
Conductivity (µS/cm)	-	-	10 770	6 280	990	430	250	11.1

TABLE A.20 CHARACTERIZATION OF SUMMERSIDE BAGHOUSE MATERIAL (831124D) AND LEACHATES

Parameter	Solids (mg/kg)		Leachates (mg/L)					
	Before Leaching	After Leaching	Cycle 1	Cycle 2	Cycle 5	Cycle 10	Cycle 20	Blank
Aluminum	30 900	54 900	< .01	< .01	< .01	< .01	4.17	< .01
Arsenic	220	369	< .005	< .005	.027	< .005	< .005	< .005
Barium	213	170	.040	< .005	< .005	.295	< .005	< .005
Beryllium	2.09	4.86	< .0005	< .0005	< .0005	< .0005	< .0005	< .0005
Boron	63.1	63.1	.066	.039	.025	.018	.038	< .004
Cadmium	15	< 1	< .01	< .01	< .01	< .01	< .01	< .01
Calcium	299 000	101 000	1 440	1 390	1 030	705	62.5	< .01
Chloride	-	-	36.6	7.5	15.1	.8	1.0	< .1
Chromium	23	29	< .01	< .01	< .01	< .01	< .01	< .01
Cobalt	< 5	< 5	< .05	< .05	< .05	< .05	< .05	< .05
Copper	29.4	51.6	< .009	< .009	< .009	< .009	< .009	< .009
Fluoride	-	-	1.9	< .1	< .1	.9	.5	< .1
Iron	75 900	143 000	.08	.13	.06	.06	.01	< .01
Lead	140	215	< .05	< .05	< .05	< .05	< .05	< .05
Lithium	30	42	-	-	-	-	-	< .01
Magnesium	9 030	15 700	< .01	< .01	< .01	< .01	.02	< .01
Manganese	635	1 220	< .01	< .01	< .01	< .01	< .01	< .01
Molybdenum	< 20	< 20	< .2	.3	< .2	.3	< .2	< .2
Nickel	47	51	.06	.07	< .05	< .05	< .05	< .05
Phosphorus	650	1 350	< .6	< .6	< .6	< .6	< .6	< .6
Potassium	5 500	7 800	< 1	3	2	3	< 1	<1
Silicon	54 800	106 000	< .05	< .05	< .05	< .05	3.56	< .05
Silver	< 5	< 5	< .005	.011	< .005	< .005	< .005	< .005
Sodium	2 100	2 200	< 1	< 1	< 1	2	< 1	<1
Strontium	60.1	76.2	1.21	.639	.227	< .001	.016	< .001
Sulphate	-	-	1 310	1 320	1 107	4	55	<1
Thorium	3.4	-	< .003	< .003	< .003	< .003	< .003	< .003
Titanium	1 090	2 210	< .005	< .005	< .005	< .005	< .005	< .005
Uranium	1.2	-	.0048	.0010	.0010	.0014	< .001	< .001
Vanadium	37.5	67.6	< .005	< .005	< .005	< .005	.028	< .005
Zinc	343	486	< .05	.06	< .05	< .05	< .05	< .05
Zirconium	24	40	< .05	< .05	< .05	< .05	< .05	< .05
Acidity	-	-	< 1	< 1	< 1	< 1	< 1	<1
Hardness	-	-	3 600	3 475	2 575	1 765	160	<1
pH (units)	-	-	12.6	12.7	12.5	12.3	11.0	7.2
TDS	-	-	4 734	4 500	3 364	1 734	174	<2
Conductivity (μS/cm)	-	-	9 150	8 830	8 270	7 000	450	11.1

TABLE A.21 pH, CONDUCTIVITY, TOTAL DISSOLVED SOLIDS, AND WEIGHT LOSS OF QUEEN'S MATERIAL (831115E) LEACHATES

	Material								
	Bed			Cyclone			Baghouse		
Cycle	pH	Cond. (μS/cm)	TDS (mg/L)	pH	Cond. (μS/cm)	TDS (mg/L)	pH	Cond. (μS/cm)	TDS (mg/L)
1	12.4	9000	4866	12.4	9160	4910	12.4	10820	5548
2	12.4	8900	4344	12.4	8980	4468	12.3	7950	3128
3	12.6	9000	4320	12.7	8300	3408	12.7	6500	1660
4	12.1	8500	4340	12.4	7500	2246	12.1	2400	614
5	12.3	8640	4344	12.3	7620	1918	11.6	1400	376
6	12.1	9000	4264	12.1	7500	1854	11.4	1020	216
7	12.1	8200	4198	12.1	7200	1918	11.3	820	266
8	12.1	8500	3910	12.1	7400	1756	11.4	740	242
9	12.1	8000	3536	12.1	7400	1874	11.4	690	226
10	12.4	7800	2724	12.4	7310	1870	11.1	640	254
11	12.1	7500	1970	11.9	7200	1804	11.3	640	228
12	12.1	7400	1848	11.9	7400	1848	11.3	590	266
13	12.1	7300	1804	12.1	7500	1826	11.3	550	268
14	12.3	7000	1714	12.1	7200	1806	11.2	540	248
15	12.3	6200	1446	12.2	7100	1844	11.3	530	270
16	12.1	1730	450	12.1	7200	1804	11.4	530	250
17	11.1	940	286	12.3	7000	1762	11.3	540	252
18	10.6	780	280	11.9	7000	1726	10.8	550	240
19	11.1	710	234	12.3	6900	1684	11.1	550	222
20	11.1	582	228	12.1	4800	1198	10.9	510	206
Initial Wt. (g)		43			43			43	
Final Wt. (g)		10			20			37	
Percent Loss		76.7			53.5			13.9	

TABLE A.22 pH, CONDUCTIVITY, TOTAL DISSOLVED SOLIDS, AND WEIGHT LOSS OF QUEEN'S MATERIAL (831122E) LEACHATES

	Material								
	Bed			Cyclone			Baghouse		
Cycle	pH	Cond. (µS/cm)	TDS (mg/L)	pH	Cond. (µS/cm)	TDS (mg/L)	pH	Cond. (µS/cm)	TDS (mg/L)
1	12.4	9030	4492	12.5	9290	4878	11.9	6580	4476
2	12.4	9010	4490	12.5	9090	4494	11.5	2590	2384
3	12.8	9000	4398	12.8	9000	4308	11.5	1700	1478
4	12.5	9000	4260	12.5	8400	3972	11.4	1050	702
5	12.4	8900	4358	12.4	8170	2860	11.1	605	394
6	12.2	9000	4250	12.2	7600	1976	11.2	550	214
7	12.1	8600	4300	12.1	7200	1846	11.1	540	260
8	12.1	8800	4196	12.1	7200	1726	11.1	530	238
9	12.1	7500	4286	12.2	7100	1690	11.1	500	234
10	12.3	7750	4294	12.4	7250	1672	11.1	480	256
11	12.3	8000	4140	12.1	7000	1612	11.1	510	216
12	11.9	3180	1888	12.1	6600	1538	10.9	460	270
13	11.5	1410	668	11.9	3300	764	10.9	430	226
14	11.5	920	346	11.7	1450	334	10.9	420	188
15	11.4	700	278	11.8	880	290	11.1	400	198
16	11.4	620	240	11.5	740	252	11.1	375	192
17	11.4	580	200	11.3	620	206	11.1	375	158
18	10.9	540	186	10.9	510	182	10.6	375	138
19	10.9	530	166	10.9	450	124	10.6	350	128
20	10.8	520	180	10.9	370	132	10.4	310	148
Initial Wt. (g)		43			43			43	
Final Wt. (g)		9			22			34	
Percent Loss		79.1			48.8			20.9	

TABLE A.23 pH, CONDUCTIVITY, TOTAL DISSOLVED SOLIDS, AND WEIGHT LOSS OF QUEEN'S MATERIAL (831124E) LEACHATES

	Material								
	Bed			Cyclone			Baghouse		
Cycle	pH	Cond. (µS/cm)	TDS (mg/L)	pH	Cond. (µS/cm)	TDS (mg/L)	pH	Cond. (µS/cm)	TDS (mg/L)
1	12.4	8980	4560	12.4	9200	4808	12.5	11390	5358
2	12.5	8860	4532	12.5	9020	4658	12.2	6700	3766
3	12.7	8900	4470	12.7	9000	4574	11.6	2300	2094
4	12.5	9000	4408	12.6	8500	4452	11.4	1670	1400
5	12.3	8850	4330	12.4	8500	4286	11.3	920	568
6	12.5	8900	4404	12.6	8300	3588	11.4	580	186
7	12.1	8900	4412	12.6	7500	2530	11.3	520	240
8	12.1	8800	4248	12.4	7400	1808	11.3	470	140
9	12.2	8200	4298	12.4	7400	1890	11.4	450	180
10	12.3	8550	4370	12.3	7450	1870	11.2	440	212
11	12.4	8000	4100	12.4	7200	1760	11.2	460	174
12	11.9	2500	1508	12.5	7200	1846	11.2	420	216
13	11.6	1280	584	12.4	7200	1826	11.2	370	184
14	11.6	860	308	12.5	7000	1788	11.1	350	154
15	11.4	660	280	12.6	6800	1672	11.1	350	184
16	11.3	590	238	12.2	2950	556	11.2	350	166
17	11.3	560	206	11.8	1280	324	11.1	360	128
18	10.9	530	170	11.3	900	256	10.9	360	124
19	10.9	530	158	11.2	770	232	10.7	350	100
20	10.9	450	174	11.1	577	212	10.3	294	120
Initial Wt. (g)		43			43			43	
Final Wt. (g)		8			17			34	
Percent Loss		81.4			60.5			20.9	

TABLE A.24 pH, CONDUCTIVITY, TOTAL DISSOLVED SOLIDS, AND WEIGHT LOSS OF QUEEN'S MATERIAL (831213E) LEACHATES

	Material								
	Bed			Cyclone			Baghouse		
Cycle	pH	Cond. (μS/cm)	TDS (mg/L)	pH	Cond. (μS/cm)	TDS (mg/L)	pH	Cond. (μS/cm)	TDS (mg/L)
1	12.4	8900	4432	12.5	9150	4782	12.4	11170	5514
2	12.4	8880	4400	12.6	8920	4576	12.1	4900	3354
3	12.6	8900	4300	12.8	8900	4480	11.8	2400	2120
4	12.6	9000	4370	12.6	8500	4310	11.5	1650	1318
5	12.3	8780	4322	12.3	8580	3636	11.4	950	604
6	12.5	8800	4194	12.6	7800	2444	11.5	650	270
7	12.5	8500	4084	12.7	7500	2088	11.5	550	298
8	12.5	8200	3810	12.5	7400	1812	11.4	530	182
9	12.5	8000	3216	12.5	7200	1860	11.4	510	218
10	12.3	8040	2566	12.4	7420	1862	11.1	475	216
11	12.4	7500	2082	12.6	7200	1784	11.3	480	176
12	12.5	7500	1884	12.6	7500	1818	11.3	440	238
13	12.5	7500	1780	12.6	7200	1794	11.3	420	204
14	12.4	7200	1716	12.7	7000	1734	11.2	400	190
15	12.6	7200	1796	12.6	6500	1540	11.3	380	192
16	12.5	7200	1706	11.8	2250	550	11.1	375	180
17	12.5	7100	1672	11.8	1100	292	11.1	375	150
18	12.3	7000	1642	11.5	780	248	11.1	380	132
19	12.3	7100	1624	11.1	650	214	10.8	370	126
20	12.2	5600	1328	11.1	544	196	10.5	325	132
Initial Wt. (g)		43			43			43	
Final Wt. (g)		9			18			33	
Percent Loss		81.4			58.1			23.3	

TABLE A.25 pH, CONDUCTIVITY, TOTAL DISSOLVED SOLIDS, AND WEIGHT LOSS OF QUEEN'S MATERIAL (831214E) LEACHATES

	Material								
	Bed			Cyclone			Baghouse		
Cycle	pH	Cond. (µS/cm)	TDS (mg/L)	pH	Cond. (µS/cm)	TDS (mg/L)	pH	Cond. (µS/cm)	TDS (mg/L)
1	12.5	8840	4400	12.6	9110	4786	12.5	10490	5460
2	12.5	8800	4470	12.6	9000	4562	12.5	8840	4384
3	12.7	8900	4376	12.8	9000	4492	12.7	7800	4120
4	12.7	8800	4310	12.7	8500	4280	12.6	7300	3598
5	12.4	8780	4374	12.6	8800	4374	11.5	2070	1302
6	12.6	8500	4208	12.7	8500	3818	11.7	1050	436
7	12.7	8200	4092	12.8	7800	2772	11.5	740	284
8	12.5	8500	3636	12.7	7400	1906	11.6	640	194
9	12.5	8200	3024	12.6	7400	1862	11.5	570	220
10	12.4	7970	2394	12.4	7480	1798	11.2	550	226
11	12.6	7500	2032	12.6	7200	1736	11.4	550	206
12	12.5	7500	1960	12.6	7300	1784	11.4	490	244
13	12.6	7200	1882	12.6	7200	1786	11.4	475	240
14	12.6	7200	1814	12.8	7200	1716	11.4	465	218
15	12.6	7200	1842	12.5	7000	1788	11.3	460	234
16	12.5	7200	1794	12.4	6800	1660	11.3	470	216
17	12.5	7000	1752	12.4	3800	906	11.3	460	194
18	12.5	7200	1784	11.8	1380	334	11.2	460	174
19	12.2	7200	1740	11.4	910	236	10.9	460	168
20	12.4	7200	1730	11.2	700	228	10.8	420	170
Initial Wt. (g)		43			43			43	
Final Wt. (g)		9			15			30	
Percent Loss		81.4			65.1			30.2	

TABLE A.26 pH, CONDUCTIVITY, TOTAL DISSOLVED SOLIDS, AND WEIGHT LOSS OF QUEEN'S MATERIAL (840105E) LEACHATES

	Material								
	Bed			Cyclone			Baghouse		
Cycle	pH	Cond. (µS/cm)	TDS (mg/L)	pH	Cond. (µS/cm)	TDS (mg/L)	pH	Cond. (µS/cm)	TDS (mg/L)
1	12.6	8990	4506	12.7	9240	4686	12.4	10770	5258
2	12.7	8820	4458	12.7	9110	4596	12.1	6280	3416
3	12.9	8600	4468	12.9	9000	4498	11.9	2350	1950
4	12.7	9000	4346	12.7	8900	4400	11.5	1650	1344
5	12.5	8920	4308	12.5	8950	4266	11.4	990	666
6	12.7	8900	4098	12.7	8100	3466	11.5	660	344
7	12.6	8600	3884	12.2	7400	2342	11.5	530	284
8	12.5	8100	3352	12.4	7100	1824	11.5	470	210
9	12.6	7800	2864	11.8	6800	1684	11.3	460	204
10	12.4	7750	2338	11.8	2050	514	11.3	430	216
11	12.7	7500	1972	11.5	1040	284	11.3	465	200
12	12.6	7500	1872	11.5	730	290	11.3	425	218
13	12.6	7300	1828	11.5	620	250	11.3	380	202
14	12.5	7300	1814	11.4	550	204	11.2	390	182
15	12.5	7200	1850	11.4	540	206	11.2	375	176
16	12.4	7200	1762	11.5	490	186	11.2	365	184
17	12.5	7000	1716	11.4	480	162	11.1	340	130
18	12.4	7000	1710	11.4	430	140	11.1	340	116
19	12.2	6500	1550	11.1	410	140	10.8	320	92
20	11.9	2130	516	10.8	340	124	10.6	250	124
Initial Wt. (g)		43			43			43	
Final Wt. (g)		10			22			33	
Percent Loss		76.7			48.8			23.3	

TABLE A.27 pH, CONDUCTIVITY, TOTAL DISSOLVED SOLIDS, AND WEIGHT LOSS OF SUMMERSIDE (831124D) LEACHATES

	Material					
	Bed			Baghouse		
Cycle	pH	Cond. (µS/cm)	TDS (mg/L)	pH	Cond. (µS/cm)	TDS (mg/L)
1	12.6	8990	4476	12.6	9150	4734
2	12.6	8850	4438	12.7	8830	4500
3	12.8	9000	4450	12.9	8500	4462
4	12.7	8500	4388	12.7	8300	4238
5	12.5	8910	4304	12.5	8270	3364
6	12.6	8500	4246	12.7	7500	1954
7	12.5	8900	4248	12.2	7000	1840
8	12.4	8500	4100	12.3	7200	1772
9	12.6	8100	3898	12.4	7000	1776
10	12.5	8130	3278	12.3	7000	1734
11	12.6	7500	2422	12.1	6100	1424
12	12.6	7300	1976	11.9	2200	534
13	12.6	7200	1786	11.9	1225	330
14	12.4	4600	1130	11.8	900	264
15	12.1	1390	352	11.7	760	248
16	11.6	890	304	11.4	690	254
17	11.6	760	262	11.4	620	213
18	11.4	710	252	11.3	580	202
19	11.1	680	228	11.1	530	158
20	11.1	570	212	11.1	450	174
Initial Wt. (g)		43			43	
Final Wt. (g)		10			24	
Percent Loss		76.7			44.2	

APPENDIX B
QUALITY CONTROL DATA

TABLE B.1 COMPARATIVE ANALYSES OF A STANDARD REFERENCE MATERIAL*

Parameter	Certified Values	Measured Values	% Recovered
Aluminum (%)	14.0	14.05	100
Arsenic	145 ± 15	146	101
Barium	1500	1365	91
Beryllium	12.0	11.8	98
Cadmium	1.0 ± 0.15	1	99
Calcium (%)	1.11 ± .01	1.03	93
Chromium	196 ± 6	185	94
Cobalt	46	42	91
Copper	118 ± 3	120	102
Iron (%)	9.4 ± .1	9.8	104
Lead	72.4 + 0.4	60.0	83
Magnesium	4500 ± 100	4580	101
Manganese	190	190	100
Nickel	127 ± 4	116	91
Potassium (%)	1.88 ± 0.6	2.02	107
Silicon (%)	22.8 ± .8	23.2	102
Sodium	1700 ± 100	1990	117
Strontium	830 ± 30	813	98
Thorium	24.7 ± 0.3	22.0	89
Titanium	8000	8560	107
Uranium	10.2 ± 0.1	10.5	103
Vanadium	300	287	96
Zinc	220 ± 10	217	99

Note: All results expressed in µg/g unless otherwise stated.

* Standard Reference Material - 1633A (Coal Fly Ash) from the National Bureau of Standards

TABLE B.2 REPRODUCIBILITY OF APBC SOLIDS MATERIAL ANALYSES BEFORE LEACHING*

Sample	Ag	Al (%)	B	Ba	Be	Ca (%)	Cd	Co	Cr	Cu	Fe (%)	K	Mg	Mn	Mo	Na	Ni	P	Pb	Si (%)	Sr	Ti	V	Zn	Zr
Queen's Bed 831213E	<5	.4440	21.9	80.0	< .05	32.2	< 1	<5	3	12.6	1.35	900	3740	597	<20	800	27	300	< 5	1.30	7.7	320	14.9	215	16
	<5	.3870	26.8	77.0	< .05	31.2	< 1	<5	3	12.1	1.38	900	3650	571	<20	1000	30	290	< 5	1.38	7.1	322	16.3	232	17
Queen's Cyclone 831213E	<5	1.31	71.1	220	.25	36.8	14	<5	2	39.7	7.88	2100	2970	659	<20	2600	37	590	90	3.33	8.7	517	35.5	858	16
	<5	1.24	61.0	209	.28	37.4	17	<5	4	39.3	7.81	2100	2900	665	<20	2500	42	620	80	3.49	8.6	527	36.1	1000	17
Queen's Baghouse 831213E	<5	5.48	196	796	5.01	14.0	56	<5	38	229	20.3	9900	3370	407	<20	13400	122	3220	865	7.85	339	3670	405	2500	60
	<5	5.12	173	811	4.80	13.8	58	<5	46	213	20.6	9700	3200	387	<20	13500	122	3000	865	7.77	323	3460	393	2390	55
Summerside Bed 831124D	<5	1.42	24.6	158	.10	44.8	< 1	<5	10	7.7	1.65	2800	5350	849	<20	1300	27	290	45	3.09	123	574	8.8	209	20
	<5	1.45	20.7	168	.13	45.2	1	<5	11	7.6	1.61	2800	5440	861	<20	1500	29	290	40	3.30	100	638	11.6	198	22
Summerside Baghouse 831124D	<5	3.09	63.1	213	2.09	29.9	15	<5	23	29.4	7.59	5500	9030	635	<20	2100	67	650	140	5.48	60.1	1090	37.5	343	29
	<5	2.98	55.3	197	2.30	31.7	20	<5	20	34.7	8.14	6000	9170	700	<20	1800	52	720	120	5.44	49.3	1220	37.8	395	26

* all results expressed as µg/g unless otherwise specified.

TABLE B.3 REPRODUCIBILITY OF LEACHED APBC SOLID MATERIAL ANALYSES*

Sample	Ag	Al (%)	B	Ba	Be	Ca (%)	Cd	Co	Cr	Cu	Fe (%)	K	Mg	Mn	Mo	Na	Ni	P	Pb	Si (%)	Sr	Ti	V	Zn	Zr
Queen's Bed 831213E	<5	2.63	117	128	1.17	28.3	<1	<5	26	56.0	7.17	2300	18100	3000	<20	2200	32	1740	15	8.0	347	1890	115	525	60
	<5	2.67	112	105	1.25	28.1	<1	<5	27	55.2	7.21	2000	18700	2940	<20	2000	32	1650	15	7.38	363	1860	111	573	56
Queen's Cyclone 831213E	<5	2.71	91.8	200	1.39	11.7	<1	<5	3	79.7	18.0	2900	5640	1000	<20	3500	47	1550	125	8.1	36.4	1180	115	1820	28
	<5	2.87	75.2	217	1.88	11.7	<1	<5	2	77.6	18.3	2900	6030	1070	<20	3700	47	1480	120	7.6	42.4	1210	115	1860	28
Queen's Baghouse 831213E	<5	6.31	124	990	8.19	7.4	<1	<5	66	256	27.6	9600	4220	502	<20	10300	129	4230	900	10.2	330	4490	430	2800	80
	<5	6.68	114	987	8.37	7.3	<1	<5	57	251	27.3	9000	4160	484	<20	11200	136	4160	950	10.2	316	4520	431	2790	88
Summerside Bed 831124D	<5	5.17	88.3	410	2.98	22.6	<1	<5	56	25.0	6.79	8700	19600	3030	<20	2400	55	1410	150	13.5	239	2620	69.6	379	71
	<5	5.78	87.8	350	2.65	20.8	<1	<5	60	24.3	6.68	9700	18900	2870	<20	2700	55	1310	170	13.5	236	3050	70.2	339	73
Summerside Baghouse 831124D	<5	5.49	63.1	170	4.86	10.1	<1	<5	29	51.6	14.3	7800	15700	1220	<20	2200	51	1350	215	10.6	76.2	2210	67.6	486	40
	<5	5.48	63.8	182	5.03	10.3	<1	<5	33	57.0	14.3	8100	15900	1220	<20	2500	53	1410	215	11.4	76.5	2210	68.8	477	42

* all results expressed as µg/g unless otherwise specified.

TABLE B.4 REPRODUCIBILITY OF LEACHATE ANALYSES*

Sample	Ag	Al	B	Ba	Be	Ca	Cd	Co	Cr	Cu	Fe	K	Mg	Mn	Mo	Na	Ni	P	Pb	Si	Sr	Th	Tl	U	V	Zn	Zr
Queen's Bed 831213E	<.005	<.01	.032	<.005	<.0005	1340	<.01	<.05	<.01	.011	.10	<1	<.01	<.01	.3	<1	.06	<.6	<.05	< .05	.262	<.003	<.005	<.001	<.005	.07	<.05
	<.005	<.01	.038	<.005	<.0005	1400	<.01	<.05	.01	.010	.08	<1	<.01	<.01	.2	<1	.07	<.6	<.05	< .05	.238	<.003	<.005	<.001	<.005	.07	<.05
Queen's Cyclone 831213E	<.005	<.01	.039	<.005	<.0005	1390	<.01	<.05	.01	<.009	.06	<1	<.01	<.01	.2	<1	.06	<.6	<.05	< .05	.532	<.003	<.005	<.001	<.005	.28	<.05
	<.005	<.01	.040	<.005	<.0005	1470	<.01	<.05	.01	<.009	.07	<1	<.01	<.01	.2	<1	.07	<.6	<.05	< .05	.537	<.003	<.005	<.001	<.005	.24	<.05
Queen's Baghouse 831213E	<.005	<.01	.297	.159	<.0005	505	<.01	<.05	.02	<.009	.05	3	.30	<.01	.3	6	<.05	<.6	<.05	8.64	.860	<.003	<.005	<.001	.231	<.05	<.05
	<.005	<.01	.312	.143	<.0005	538	<.01	<.05	.01	<.009	.04	3	.31	<.01	.3	7	<.05	<.6	<.05	9.20	.891	<.003	<.005	<.001	.246	<.05	<.05
Summerside Bed 831124D	<.005	<.01	.031	<.005	<.0005	1240	<.01	<.05	.01	.012	.07	<1	<.01	<.01	<.2	<1	<.05	<.6	<.05	< .05	.443	<.003	<.005	<.001	<.005	.06	<.05
	<.005	<.01	.026	<.005	<.0005	1280	<.01	<.05	.01	.016	.08	<1	<.01	<.01	<.2	<1	<.05	<.6	<.05	< .05	.401	<.003	<.005	<.001	<.005	.07	<.05
Summerside Baghouse 831124D	<.005	<.01	.032	<.005	<.0005	1350	<.01	<.05	.01	.009	.06	<1	<.01	<.01	<.2	<1	<.05	<.6	<.05	< .05	.387	<.003	<.005	.0010	<.005	.06	<.05
	<.005	<.01	.027	<.005	<.0005	1350	<.01	<.05	.01	.015	.08	<1	<.01	<.01	<.2	<1	<.05	<.6	<.05	< .05	.552	<.003	<.005	.0010	<.005	.06	<.05

* all results expressed as mg/L

TABLE B.5 QUALITY ASSURANCE FOR SPIKED AFBC LEACHATE ANALYSES

Parameter	Detection Limits (mg/L)	Sample Description*	Initial Value (mg/L)	Spike Added (mg/L)	Measured Value (mg/L)	Expected Value (mg/L)	% Recovery
Aluminum	< .01	OBH 831115E	< .01	0.50	0.57	0.50	114
		OBH 831122E	< .01	1.00	1.09	1.00	109
		B	< .01	4.33	4.52	4.33	96
Calcium	< .01	OBH 831122E	382	45	419	427	98
		OBH 840105E	1250	450	1680	1700	99
		B	< .01	43	40.3	43	94
Cadmium	< .01	OCL 831115E	< .01	.05	.04	.05	80
		B	< .01	.09	.09	.09	100
Chromium	< .01	OBH 831213E	< .01	.05	.03	.05	60
		B	< .01	.25	.23	.25	92
Copper	< .009	OBH 831124E	.013	.025	.031	.038	82
		OBH 831213E	.010	.500	.484	.510	95
		B	< .009	.430	.455	.430	105
Iron	< .01	OBH 831214E	.02	.10	.13	.12	108
		OBH 831122E	.04	.05	.08	.09	89
		B	< .01	.43	.47	.43	109
Potassium	<1	QCL 831213E	< 1	4	2	4	50
		OBH 840105E	3	45	42	48	88
		B	< 1	4	4	4	100
Magnesium	< .01	OBH 831122E	.08	.50	.67	.58	116
		B	< .01	1.75	1.57	1.75	90
Manganese	< .01	OBH 831213E	< .01	.10	.08	.10	80
		B	< .01	.48	.42	.48	88
Sodium	<1	OBH 831115E	8	20	26	28	93
		OBH 831124E	6	90	88	96	92
		B	< 1	25	28	25	112
Silicon	< .05	OBH 831122E	9.51	10.0	19.7	19.51	101
		OBH 840105E	3.15	.50	3.42	3.65	94
		B	< 0.5	8.65	8.53	8.65	99
Zinc	< .05	OBM 831124E	.07	.10	.16	.17	94
		OCL 831124E	.11	1.00	1.00	1.11	90
		B	< .05	.87	.84	.87	97

* Note: all samples which were spiked were from the third leaching cycle

Description:
1. OBH - Queen's Baghouse
2. QCL - Queen's Cyclone
3. OBM - Queen's Bed Material
4. B - Blank D.I. Water

TABLE B.6 CALCIUM CONTENT OF FRESH AFBC SAMPLES (Percent)

Material	Analytical Method*	Queen's 831115E	831122E	831124E	831213E	831214E	840105E	Summerside 831124D
Bed	AA (Dearborn)	42.0	37.0	37.0	46.5	44.0	43.5	36.0
	AA (WTC)	46.1	38.5	39.3	46.9	50.4	46.9	47.2
	ICAP	45.4	40.4	42.1	55.2	51.6	45.7	44.8
	XRF	43.7	35.2	39.8	47.1	44.8	42.5	37.2
	NA	43.3 ± 1.2	38.4 ± 1.2	39.1 ± 1.0	48.7 ±1.4	49.5 ± 1.5	44.0 ± 1.2	40.0 ± 1.3
	Average	44.1	37.9	39.5	48.9	48.1	44.5	41.0
Cyclone	AA (Dearborn)	41.2	30.0	34.3	33.4	35.5	25.2	
	AA (WTC)	45.0	32.3	37.6	38.6	40.6	29.5	
	ICAP	46.5	31.2	37.3	36.8	40.7	27.9	
	XRF	44.5	30.7	33.5	32.5	36.7	25.0	
	NA	42.0 ± 1.2	30.0 ± 1.1	37.3 ± 1.1	-	-	-	
	Average	43.8	30.8	36.0	35.3	38.4	26.9	
Baghouse	AA (Dearborn)	18.8	10.4	11.8	13.3	18.5	11.8	27.8
	AA (WTC)	15.8	9.1	12.1	11.6	17.9	8.9	30.0
	ICAP	20.2	10.1	12.3	14.0	20.9	12.1	29.9
	XRF	-	-	-	12.2	-	10.8	28.4
	NA	18.4 ± 0.9	10.3 ± 0.7	13.1 ± 0.7	-	-	-	-
	Average	18.3	10.0	12.3	12.8	19.1	10.9	29.0

* AA = Atomic Absorption (Dearborn and WTC Laboratories)
ICAP = Inductively Coupled Argon Plasma Spectroscopy
XRF = X-Ray Fluorescence
NA = Neutron Activation (± 1 Standard Deviation)

TABLE B.7 TOTAL SULPHUR CONTENT OF FRESH AFBC SAMPLES (Percent)

Material	Laboratory	Queen's						Summerside
		831115E	831122E	831124E	831213E	831214E	840105E	831124D
Bed	WTC	13.24	15.51	16.21	11.74	11.34	10.25	11.46
	Queen's	10.39	12.63	12.48	9.20	8.97	8.28	-
	Dearborn	10.88	13.20	13.60	9.24	9.48	8.48	10.08
Cyclone	WTC	4.43	6.90	8.42	7.18	8.13	8.06	
	Queen's	3.83	5.58	6.94	5.73	6.88	6.84	
	Dearborn	3.60	5.60	7.00	5.88	6.68	6.88	
Baghouse	WTC	4.24	4.66	5.45	5.09	7.10	5.20	6.89
	Queen's	4.00	4.55	4.56	4.42	5.55	4.57	-
	Dearborn	3.68	4.28	4.48	4.60	5.88	4.20	5.88

Run Number = Year Month Day Coal (E = Evans, D = Devco)

Analytical Methods Used: WTC = Atomic Absorption
Queen's = Vanadium Pentoxide Used As Catalyst
Dearborn = Alkaline Fusion and Wet Chemistry